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AIR FORCE SYSTEMS COMMAND

EROSION OF BLADES IN STEAM TURBINES

By

B. S. Dorogov

FOREIGN TECHNOLOGY DIVISION

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EROSION OF BLADES IN STEAM TURBINES

By: B. S. Dorogov

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ABSTRACT: This book is intended for technical personnel of design bureaus and plants and for persons concerned with problems of erosions; it may also be used by senior students in technical schools of higher education and technicians of corresponding specialties. It is a review of the present state of the problem of erosion of turbine blades based on papers published on different aspects of the problems in various countries. The causes and characteristics of the erosion of steam turbine blades, factors influencing erosion, and methods for preventing erosion are studied. The results of investigations of the erosion resistance of different metals are presented. The analogy between the erosion damage by cavitation and by impingement of drops on the surface is analyzed and the mechanism of erosion damage is investigated. English Translation: 75 pages.

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}
rot	curl
lg	log

This book examines causes and peculiarities of erosion damage of blades of steam turbines, factors affecting erosion and methods of preventing erosion. Results of investigations of erosion resistance of different metals by various methods are given, the analogy between erosion damage of parts during cavitation and under the impact of droplets on the surface of the part is analyzed, and the mechanism of erosional damage is examined.

The book is a survey of the contemporary state of the question of erosion of turbine blades and is written on the basis of articles published in various countries on separate aspects of the problem.

The book is intended for workers in design office and plants and persons interested in the questions of erosion, and also students of senior courses of corresponding specialties of higher educational institutions and technical schools.

INTRODUCTION

The specific damage of parts of steam turbines appearing under the action of multiple impacts of droplets of a condensate is called erosion. Mainly rotor blade of the last stages of condensation turbines are subject to erosion. Sometimes erosion damage is so great that it can put the turbine out of commission.

In recent years interest toward investigation of turbines working on moist vapor, and in particular, methods of preventing erosion was noticeably intensified in connection with development of atomic and geothermic power plants. In these installations superheating of steam as it enters the turbine is small, in consequence of which a considerable part of the stages works in a region of moist vapor.

The periodic press publishes many articles in which specific sides of the problem of erosion are considered; however there are very few works illustrating the problem of erosion as a whole or embracing the wide circle questions connected with erosion of steam turbine blades. Among prewar works we note investigations of L. I. Dekhtyarev [1 and 2] and the large article of Pohl [3]. Relatively recently the survey articles of Preiskorn [4] and Millies [122] were published. However articles [1, 2, and 3] are dated and the scope of earlier published materials in articles [4 and 122] is insufficient. In particular they do not analyze information pertaining to investigation of the nature of erosion damage, do not examine methods and results of investigations of erosion resistance of materials, and works published in the Russian language are not examined at all. Postwar publications of generalized works on erosion of turbine blades in the

Russian language were not found. In the widely known major works of the greatest Soviet specialists on steam turbines [5, 6 and 7] questions of erosion receive in all 2-3 pages each.

The author has tried to give a general picture of the contemporary state of the problem of erosion, based on many works on separate aspects of this question. The book considers features of erosion wear in steam turbines, means of protecting blades against erosion, methods and results of tests on erosion resistance of various materials. Much attention is given the analysis of works related to the nature of erosion damage under liquid-drop impact. Generalization of results obtained by Kornefeld and Suvorow [8] and results of subseqeunt less-known works in which was considered the impact of a drop on the surface of a solid body [9] and others, permitted showing a direct connection between erosion under liquid-drop impact and cavitation erosion, not being limited to a general consideration of the analogy of the character of destruction during cavitation and liquid-drop impact of liquids as were authors of many earlier works. The probable mechanism of damage of a solid body under liquid-drop impact is described.

The book is intended for a wide circle of readers. It can serve as an aid for students of senior courses of corresponding power specialties inasmuch as it gives a detailed systematic description of erosion. The book will be useful for designing bureau and plant workers inasmuch as it gives a summary of results of works published in recent years on methods of protection of blades from erosion, and gives extensive information about comparative erosion resistance of different metals used not only in turbine building. Finally, the book can be useful both for persons investigating turbines working on vapor and for persons investigating damage of parts under the action moving liquid (erosion) in other machines. For this group of readers the book will present interest because of the detailed biographical survey list of the contemporary[1] state of basic questions connected with the study of erosion.

The author expresses gratitude to Doctor of Technical Sciences V. Kh. Abiants and Candidate of Technical Sciences Yu. G. Zhulev for remarks made in reading the manuscript. The author thanks Engineer K. M. Kaminuskiy and Technician L. S. Fedotov for technical help.

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[1]Work on the book was completed at the end of 1963. This fast limits consideration of published works.

C H A P T E R   O N E

CONDENSATION OF VAPOR AND IMPACTS OF DROPLETS OF CONDENSATE AS A CAUSE OF EROSION DAMAGE OF BLADES

1. Condensation of Vapor in Turbine

It has been established that erosion of blades of steam turbines occurs from impacts of droplets of condensate against blade surfaces. Therefore in order to understand how and why these impacts occur, it is necessary to note the peculiarities which accompany condensation of vapor and character of movement of condensate in the flow-through part of a turbine.

The investigation of vapor-liquid phase transitions has occupied many scientists starting from V. Kel'vin and R. Gel'mgol'ets. Condensation in steam turbines was studied by A. Stodola [10]. In recent years investigation of this question received considerable attention both in connection with study of steam turbines [11-15] and in a wider plan including flow in hypersonic wind tunnels. A good survey of investigations of the phenomenon of condensation during a flow with high speeds is given in [16]. Possibilities of theoretical investigation of condensation have been considerably expanded with the use of electronic computers [17 and 18]. An exhaustive theory of condensation as yet has not been developed.

For the beginning of condensation in a turbine it is insufficient that during expansion of vapor in interblade channels a line of saturation corresponding to flat boundary of steam and liquid phases is attained, since equilibrium condensation corresponding to this line is possible only in the presence of a liquid phase. Condensation during flow of vapor in a turbine occurs on incipient nuclei of condensation if their dimension exceeds critical. An accumulation of molecules,

inadventently forming during chaotic thermal motion serve as these nuclei in conditions of flow of well purified vapor in a turbine, when presence of outside particles is almost excluded. Such accumulations of molecules always exist, not only in supercooled (supersaturated) but also in superheated steam. In examining condensation it is usually assumed that nuclei of condensation have the form of a sphere. Critical radius of nucleus $r_{кр}$ is determined by Kelvin's equation, which constitutes thermodynamic dependence of pressure p of saturated vapor on boundary of coexisting phases on the curvature $(1/r_{кр})$ of the interface and parameters of the condensed substance:

$$\ln\left(\frac{p}{p_\infty}\right)=\frac{2\sigma}{\rho_ж R T r_{кр}}, \qquad (1)$$

where p_∞ – pressure of saturation above flat surface at temperature T;

σ – surface tension;

$\rho_ж$ – density of liquid phase;

R – gas constant.

Ratio p/p_∞ is called the degree of supersaturation. Equation (1) shows that if the interface of vapor and liquid has curvature $(1/r_{кр})$, pressure p of vapor in equilibrium state at given temperature T considerably exceeds pressure p_∞, corresponding to equilibrium state for flat interface. At assigned pressure p temperature T, corresponding to equilibrium state at the interface having curvature $1/r_{кр}$, will be lower than equilibrium temperature T_∞, corresponding to a flat interface. Difference of temperatures $\Delta T = T_\infty - T$ is called the degree of supercooling.

To calculate magnitude of degree of supercooling at assigned T_∞, it is convenient to use Kelvin's formula in the form proposed by Ya. I. Frenkel:

$$\ln\frac{T_\infty}{T}=\frac{2\sigma v_B}{r_{исп} r_{кр}}; \qquad (2)$$

where v_B – molecular volume of liquid phase;

$r_{исп}$ – latent heat of vaporization; remaining designations are the same as in formula (1).

In superheated steam distribution with respect to dimensions of spontaneously formed small drops of liquid is stable [16] and the number of drops of defined radius, according to the formula of Gibbs, exponentially decreases with increase of radius. If vapor is in the supercooled (supersaturated) state distribution of drops with respect to dimensions is unstable and the number of drops of given radius

increases with increase of radius.

Theories exist which, upon defined assumptions, permit calculating rate of formation of drops of critical dimension in supercooled vapor [16]. It has been proven that rate of formation of drops sharply increases with increase of degree of supercooling at a certain degree of supercooling, when conditions will be created for formation of very small drops consisting of a comparatively small number of molecules an avalanche-type process of condensation begins, as a result of which supercooling of vapor is very rapidly eliminated. A so-called jump of condensation can appear (for instance, during expansion of vapor in a Laval nozzle).

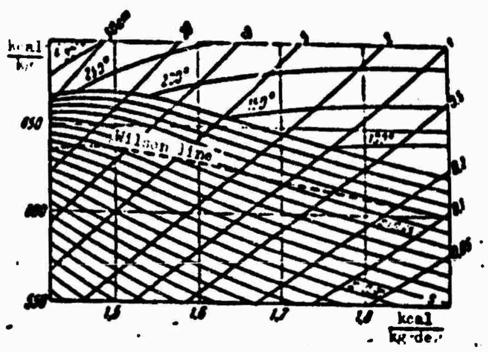

Fig. 1. Supersaturation boundary (Wilson line) on an is-diagram of water vapor.

An approximate method of calculation of the boundary of supercooling (Wilson line) during achievement of which the condensation process begins is presented in work Millies [122]. Calculation is according to the method of successive approximations using the Kelvin equation (1) and the equation of heat balance, assuming that the average diameter of drops when the vapor state corresponds to a Wilson line, is $5.3 \cdot 10^{-8}$ cm. The Wilson line calculated by Millies [122] on the is-diagram of water vapor is represented in Fig. 1, from which one may see that the Wilson line corresponds to degree of vapor dryness $x = 0.93$-0.97.

An important factor influencing delay of condensation during flow in nozzle is rate of temperature change of substance inside nozzle. Waggoner [7] and Smelt [16] found that the degree of supercooling ΔT increases with increase of gradient of temperature along axis of nozzle. During investigations of the flow of moist vapor in an axially symmetric nozzle, conducted at the department of steam and gas turbines [MEI] (МЭИ), it was shown that supercooling $\Delta T = T_H - T$ (where T_H – temperature of saturation, corresponding to given pressure; T – temperature of supercooling, calculated isoentropically at $\kappa = 1.3$) of vapor before jump of condensation is a simple function of time τ of expansion of supercooled vapor from the upper bound of the curve to the jump of condensation. This dependence, taken from the article of M. Ye. Deych, V. F. Stepanchuk, and others, [123] is shown in Fig. 2.

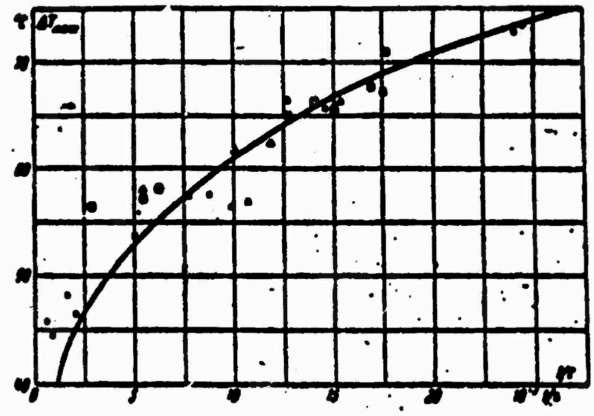

Fig. 2. Dependence of supercooling ΔT on time τ of expansion of supercooled vapor from upper boundary of curve to jump of condensation during expansion of moist vapor in nozzle.

2. Character of Motion of Condensate in Flow-Through Part of Steam Turbine

Let us consider character of motion of condensate in the flow-through part of a steam turbine. After condensation of vapor a drop of condensate was formed under the action of forces of inertia concentrated on surface of parts forming flow-through part of turbine. During motion of moist vapor in the region of the nozzle box the greatest part of the condensate collects on the concave surface of nozzle blades (Fig. 3).

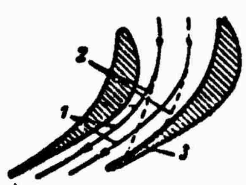

Fig. 3. Separation of vapor on blades of nozzle box. 1 – path of vapor; 2 – path of condensate; 3 – layer of condensate.

Results of experimental investigation of the motion of a condensate in a nozzle box of a turbine on special installation making it possible to visualize flow and to map the flows were published in [19]. The authors established that a condensate flows in the form of a layer along the whole blade. Investigation of its structure showed that the layer is binary: along the blades surface slowly flows a film of water, and above the film a layer with a large number of drops. With increase of speed of vapor on leaving the box up to $M_1 \approx 1.1$ thickness of binary layer decreases, and with increase of initial humidity it increases (Fig. 4). On the convex surface of the profile the film is considerably thinner than on the concave surface, where more than 2/3 of the liquid-drop moisture contained in the flow collects. From trailing edges of blades condensate flows

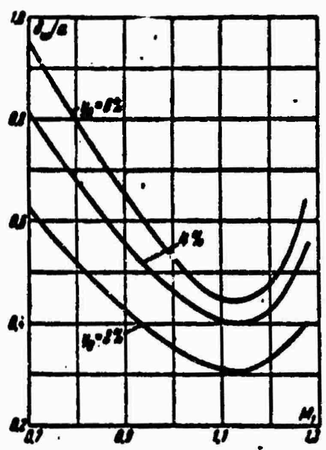

Fig. 4. Change of relative thickness of binary layer δ_w/a for profile [TN2] (TH2) depending upon M_1 number and initial vapor moisture. δ_w – thickness of binary layer; a – width of throat of vane channel.

not in a uniform film but the form of isolated streams atomized by the flow. Character of distribution of these streams with respect to height of blade indicates irregularity of thickness of film with respect to height of blade and nonstationarity of flow of film (surface of film is wavy). One cause determining irregularity of thickness of film with respect to height of blade is secondary flow in the box. Converging from trailing edges of blades flows of condensate are atomized and are eroded (Fig. 5).

With those same [19] tests of a bank of nozzle blades on moist vapor at near-critical conditions, appearance of jumps of condensation near nozzle box exhaust was fixed.

In the axial clearance between nozzle box and rotor occurs acceleration of secondary drops formed when the film of condensate descending from blades of the rotor splits, and thrusting of drops onto the peripheral surface due to the peripheral component of speed which is imparted to the flow in the nozzle box. The question of motion of drops in the axial clearance is considered in greater detail in the following section.

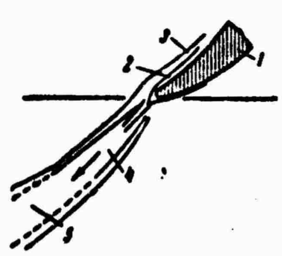

Fig. 5. Diagram of motion of moisture on nozzle box exhaust. 1 – blade; 2 – film of liquid; 3 – liquid-drop layer; 4 – zone of atomization; 5 – liquid-drop trace.

Drops falling onto the surface of the rotor are directed toward the housing along the external surface of blades due to rotation of rotor in accordance with Fig. 6. Character of motion of condensate can be judged by traces which sometimes are distinctly noticeable on concave surface of blades of rotor [3, 20 and 21].

An attempt at theoretical investigation of the motion of condensate along surface of blades of rotor under a number of simplifying assumptions was undertaken by Millies [122]. Due to the thrust of condensate against surface of blades of rotor, distribution of moisture over the blade after the rotor turns out to be very nonuniform. A larger part of the moisture concentrates near periphery of blade. A typical map distribution

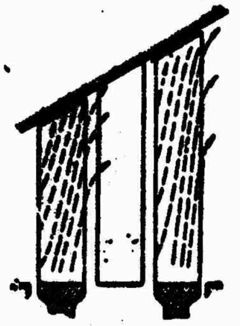

Fig. 6. Thrusting of drops of condensate in region of boundary layer of blades of rotor.
-- -- -- -- path of drops of condensate.

vapor flow moisture after the rotor of a turbine stage is given in Fig. 7. These data were obtained on an experimental turbine at the department of steam and gas turbines MEI by V. A. Golovin and F. V. Kazintsev. The investigated stage was a model of the last stage of the turbine [PVK-200] (ПВК-200) ($l_{р.к}$ = 209 mm and $d_{ср}/l_{р.к}$ = 2.8). Distribution of moisture over the blade was measured with a moving capacitive probe. As can be seen from Fig. 7, the ratio u/c_1 noticeably influences distribution of moisture over the blade. One may see also that the shroud wire is a concentrator of moisture.

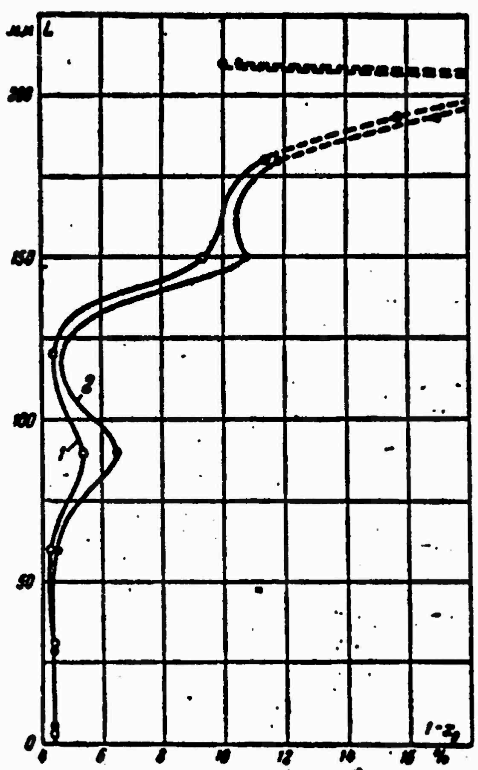

Fig. 7. Distribution of vapor moisture over blade, measured on rotor exit of turbine at uniform vapor moisture on entrance $1 - x_0$ = 4.8%; shroud bands are fixed at L = 90 and 190 mm. 1 – measured at u/c_1 = 0.21; 2 – measured at u/c_1 = = 0.48.

Water dropped from blades of rotor onto the housing covers its internal surface with a solid annular sheet [3 and 22]. In certain cases all over the

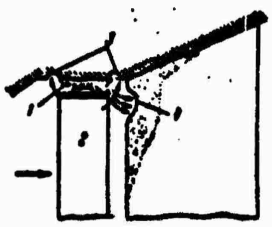

Fig. 8. Sheet of condensate on housing above rotor of turbine and erosive influence of drops from this sheet onto blades of rotor. 1 - sheet of condensate; 2 - blade of rotor; 3 - groove on housing; 4 - erosion zone nozzle box blade.

housing opposite leading and trailing edges of shrouded blades, due to erosion deep grooves are formed (Fig. 8). Between grooves is characteristic erosion in the form of furrows whose clear orientation testifies that the water ring on the housing revolves in the direction of rotation of the rotor. Rotation of water ring on housing is caused by the fact that drops of water from the surface of blades of the rotor have a peripheral component of velocity very close to the peripheral velocity of rotation of blades. This was established as a result of treatment of stroboscopic investigations of the movement of particles of water dropped from the surface of blades of the rotor [122 and 124].

The ring-shaped sheet of water on the housing simultaneously with rotation advances downwards with respect to the flow. If after the rotor there is an efficient moisture removal arrangement (see Chapter 4), a considerable part of the condensate from the ring-shaped sheet is removed from the flow-through part of the turbine. If, however, there is no moisture removal arrangement, the water ring strikes guide vane blades of the following stage. Water from it can go toward the center of the blades, causing erosion damage of blades of the rotor of the following stage (Fig. 9) can immediately atomize, enter the main flow and cause local erosion of blades of nozzle box (Fig. 8). Character of movement of condensate from revolving water ring in guide zone depends on configuration of the component of flow-through part of turbine. In particular, if blades of guide have a long section close to the peripheral direction and there is no sharp break of the configuration of the housing, the main mass of the condensate from the revolving water ring can continue motion near the housing [122]. Then erosion in places shown in Figs. 8 and 9 can not occur.

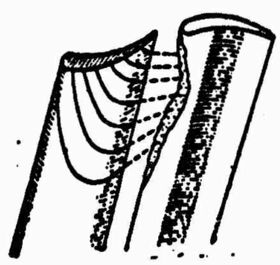

Fig. 9. Erosion of blades of rotor from impacts of droplets thrown-out from revolving water ring formed above rotor of preceding stage.

Part of the water falling on the surface of the rotor can, under the action of Coriolis force, be detached from the blade surface, and in the form of drops enter the vapor flow (Fig. 10) [122]. Breakaway of drops from surface of blade

will occur similarly to the way runoff of drops from the lower surface of a horizontal plate occurs under the action of gravity.

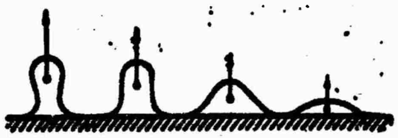

Fig. 10. Breakaway of drops from surface of blades of rotor under the action of Coriolis force.

3. Dimensions of Drops and Their Motion in the Axial Clearance Between Nozzle Box and Rotor

Streams of condensate descend from trailing edges of nozzle box blades at low speed with respect to vapor. In the axial clearance between the nozzle box and the rotor the stream breaks up into small droplets which are attracted and accelerated by the flow of vapor. Intensity of erosion damage of rotor blades in considerable degree depends on dimensions and speed of drops striking the blades. Let us consider what factors determine these magnitudes.

Investigation of atomization of drops in a gas flow (vapor) is the subject of a large number of works [23-31] et al. It has been established [27] that basic criteria affecting disintegration of a drop in a vapor flow (gas) are Weber number

$$W = \frac{\rho_{\Pi} c_{\text{отн}}^2 r}{\sigma} \tag{3}$$

and stability number

$$\Gamma = \frac{\mu_{\text{ж}}^2}{r \rho_{\text{ж}} \sigma}, \tag{4}$$

where c_{OTH} – speed of drop with respect to flow of vapor; ρ_{Π} – vapor density; $\rho_{\text{ж}} = \gamma_{\text{ж}}/g$ – density of liquid; r – radius of drop; $\mu_{\text{ж}}$ – liquid viscosity; σ – surface tension.

For low-viscosity liquids (for example, for water) Weber number (W) plays a basic role. Disintegration of drops occurs if Weber number is larger than critical value $W > W_{\text{Kp}}$. Knowing critical Weber number the biggest diameter of drops after atomization can be found.

Different authors, proceeding from results of theoretical and experimental investigations, propose different calculated values for critical Weber number.

For example, Prandtl' [25], considering the drop as a sphere, and comparing the force of aerodynamic drag appearing during the movement of a drop in the flow with internal pressure in the drop, caused by forces of surface tension, on the basis of results of experiments finds that $W_{кр} = 3.75$. According to Volynskiy [24] and Lyshevskiy [28] $W_{кр} = 6\text{-}7$, according to data of Bukhman [31] $W_{кр} = 1.3\text{-}1.8$.

For determination of diameter of drops atomized by vapor flow frequently the simplified empirical formula of Nukiyama-Tanazava is used, checked in a wide range of variation of parameters of flow [26 and 32]:

$$d = \frac{1.83}{c_{отн}}\sqrt{\frac{\sigma}{\gamma_п}}. \tag{5}$$

Result of calculation of diameters of drops by this formula are represented in Fig. 11. With the help of this figure it is possible to judge the order of magnitude of diameter of secondary drops, which were formed upon full atomization of the film of water converging from blades of the nozzle box. From the figure one may see also that with increase of speed of vapor, other things being equal, diameters of drops noticeably decrease. Decrease of diameter of drops occurs also upon increase of vapor pressure (due to change of σ).

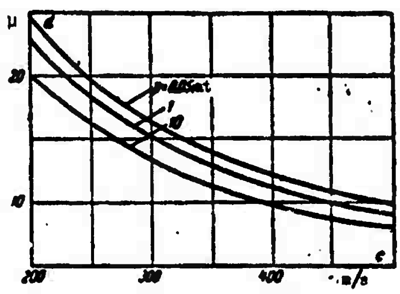

Fig. 11. Diameter of water droplets atomized by a flow of vapor, depending upon speed and vapor pressure.

Solving mechanics equation

$$m\frac{d^2 s}{dt^2} = c_x F_{мид}\frac{\rho_п (c_п - c_ж)^2}{2} \tag{6}$$

taking into account conditions determining the dimension of drops dependence of speeds of drops $c_ж$ on parameters characterizing flow of vapor in axial clearance of turbine can be found. In equation (6): m – mass of drop; s – path of drop; t – time; $c_п$ – vapor speed; $c_ж$ – speed of drop; $F_{мид}$ – area of middle of drop; $\rho_п$ – vapor density; c_x – drag coefficient, depending on Re number and form of drop.[1]

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[1] In the majority of investigations of movement of drops in a vapor flow, it is assumed that the drop has the form of a sphere. However, in certain recently published works (see for instance [34]) it is shown that in a defined region of Re numbers, a drop can no longer be considered as spherical, and the dependences $c_x = f(Re)$ are found, taking into account deformation of drop. Investigation of motion of drops in a gas flow, taking into account definitized dependence $c_x = f(Re)$, is given in [33].

Investigation of motion drops of liquid in a flow of vapor (gas) and development of methods of solving an equation of type (6) is the subject of a large number of articles. Among the first publications on this subject it is necessary to note the works of Freudenreich [23] and L. I. Dekhtyarev [1]. There then appeared a series of articles in which attempts to definitize earlier obtained results [32-36] and others were started.

During calculation of speed of drops in the axial clearance between nozzle box and rotor usually it is assumed that acceleration of drop by vapor flow starts from zero relative speed in the section corresponding to trailing edges of nozzle box. Calculations show that the most intense increase of speed occurs on initial acceleration phase. Then growth of speed is delayed. However, with increase of path of acceleration s (axial clearance) speed of a drop continuously increases. The speed of a drop at a fixed magnitude of axial clearance will be greater the greater the speed and vapor density in the clearance. Small drops are more easily and more quickly accelerated by vapor flow than the bigger drops. Qualitatively these dependences are illustrated on Fig. 12 copied from [1]. As becomes clear from further consideration, the shown peculiarities of motion of drops in the axial clearance can be very significant for intensity of erosion damage of rotor blades.

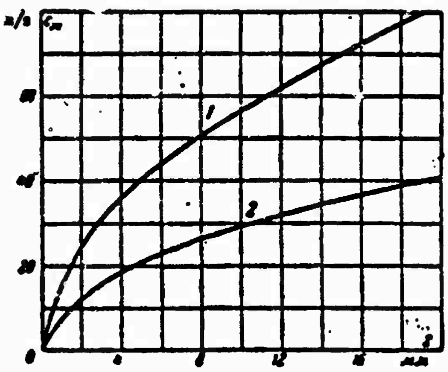


Fig. 12. Dependence of absolute speed of drops $c_{ж}$ on length of acceleration s and speed of vapor in clearance $c_{п}$ at p = 0.5 at. 1 – $c_{п}$ = 500 m/s; 2 – $c_{п}$ = 400 m/s.

Determination of speed of drops on rotor entrance sometimes can be made according to traces of erosion on blades, knowing their spacing, peripheral velocity of rotation of rotor and direction of absolute velocity of drops on rotor exit (angle α_1). The boundary of erosion wear and spacing of blades determine direction of relative speed of drops. Drawing from point 0 two lines indicating direction of absolute $c_{ж}$ and relative speed $w_{ж}$ and closing the velocity triangle by the vector of peripheral velocity u, magnitude and direction of which are known (Fig. 13), it is possible to find magnitude of absolute $c_{ж}$ and relative $w_{ж}$ of the velocity of a drop. Corresponding appraisals show that for condensation

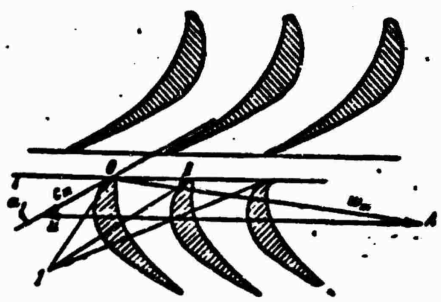


Fig. 13. Velocity triangle of a drop of water; line OA from nose of bucket O goes through point B of end of zone of erosion of neighboring bucket. 1 – zone of erosion.

turbines working on steam at low pressures on the exhaust [usually less than 0.1 at) velocity $c_ж$ attains several tens of meters per second in all, i.e., approximately an order less than speed of vapor and the speed of drops with respect to blade of rotor $w_ж$ is of the same order as the peripheral velocity of rotation of the rotor u, i.e., is sufficiently great. Appraisals conducted for the last stage of turbine [VKT-100] (ВКТ-100) of the Kharkov turbine plant [37], give $c_ж = 52$ m/s.

As was already mentioned, in the axial clearance between the nozzle box and the rotor occurs separation of drops of moisture on internal surface of turbine housing. Let us consider this phenomenon, proceeding from a simplified presentation about movement of a drop in the axial clearance.

Considering that after leaving the nozzle box on radius r at angle α_1 drops move along the straight line located in the plane tangent to circumference of radius r (see [38]), it is easy to obtain the formula for determination of magnitude of axial clearance S at which all drops coming from the nozzle box, not reaching the rotor, will fall onto the internal surface of the housing

$$S = \mathrm{tg}\,\alpha_1 \sqrt{l_{c.a} d_{cp}}. \qquad (7)$$

Formula (7) shows that the magnitude of the axial clearance in which full separation of drops on the housing depends only on the angle of departure of flow from nozzle box α_1, height of blade nozzle box $l_{c.a}$ and average diameter of nozzle box d_{cp}. More detailed strict investigation of this question, conducted later using an equation of type (6) showed that length of zone of full separation indeed weakly depends on dimensions of separated particles and parameters of vapor flow in axial clearance. Formula (7), obtained by proceeding from rough ideas about motion of particles of moisture in the clearance gives a true order of magnitude of zone of full separation S. Calculation by this formula can show that in the axial clearance, equal to height of blade of nozzle box, and at $\alpha_1 < 20°$ practically all moisture will "thrust" onto the housing.

4. Origin of Erosion and Brief Characteristics of Erosion Damage of Blades of Steam Turbines

Leading edges of rotor blades of the last stages of condensation turbines are the most subject to erosion. Typical erosion maps are shown in Fig. 14, taken from [22].

Fig. 14. Erosion wear of blades of last stages of a steam turbine.

Origin of erosion is easy to grasp from consideration of Fig. 15. On this figure are shown velocity triangles on rotor entrance for vapor (absolute velocity $c_п$, relative to $w_п$) and for drops of condensate (correspondingly $c_ж$ and $w_ж$). As was already shown velocity of drops of condensate $c_ж$ is significantly less than speed of vapor $c_п$. Therefore drops will strike in back of blades of rotor in region of leading edge with relative velocity $w_ж$, direction of which sharply differs from direction of velocity $w_п$ (Fig. 15). Under the action of these blows erosion damage of blade metal occurs. Over a defined period of time the blade surface becomes rough, then on blade erosion pits appear in the form of cavities interspersed with projections. Sometimes the blade surface becomes similar to a sponge with large gaps. During prolonged work in conditions of moist vapor erosion wear of blade in certain places can seize a considerable part of the chord line (see, for example, blade No. 3 in Fig. 14) and lead to breaking away of blade end.

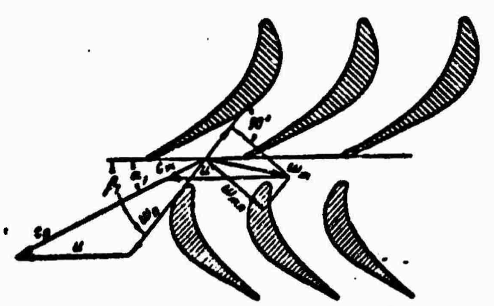


Fig. 15. Sections of buckets and velocity triangles on the stage exhaust.

Intensity of erosion is strongly influenced by magnitude of normal component $w_{ж.n}$ of relative speed of drops $w_ж$ upon impact against blade [2]. The quantity $w_{ж.n}$ is a function of peripheral velocity of rotation of rotor u, angle of entrance into rotor blades β_1, absolute velocity of vapor $c_п$ its density and magnitude of clearance S between guides and rotor blades. By simple construction of velocity triangles it is easy to verify that the larger the peripheral velocity u and the angle of incidence β_1, the bigger at other equal conditions is normal component of velocity of a drop $w_{ж.n}$, i.e., the greater the

force of the impact of a drop on a blade. Increase of vapor $c_П$ speed, its density and magnitude of axial clearance between nozzle box and rotor leads to the fact that a drop in the clearance accelerates more strongly, i.e., its absolute velocity $c_ж$ is increased (see above § 3) and force of impact of drop against blade decreases together with decrease of normal component of speed of drop[1] $w_{ж.n}$.

From the above it is clear that with increase of ratio $(u/c_П)$ conditions for appearance of erosion become more favorable. All considered parameters u, β_1, $c_П$ and $u/c_П$, as a rule for impulse-type turbines, occur more favorably than for reactive turbines. Therefore in many works [2, 3, 12, 21, 39, 40, 122, and others] it is indicated that active stages are less subject to erosi than reactive stages.

In [39] one more advantage of impulse-type turbines ove reactive with respect to erosion is noted. Considering the change of direction relative to velocity of drops upon change of peripheral velocity u, the author shows that in reactive stages the angle of this change will be less than in active stages (in considered examples 2 and 10° corre pondingly). Consequently impacts of d ops in reactive stages will be distributed over a smaller area than in active stages, i.e., the impact influence of water per 1 cm^2 of blade surface in reactive stages will be greater than in active stages.

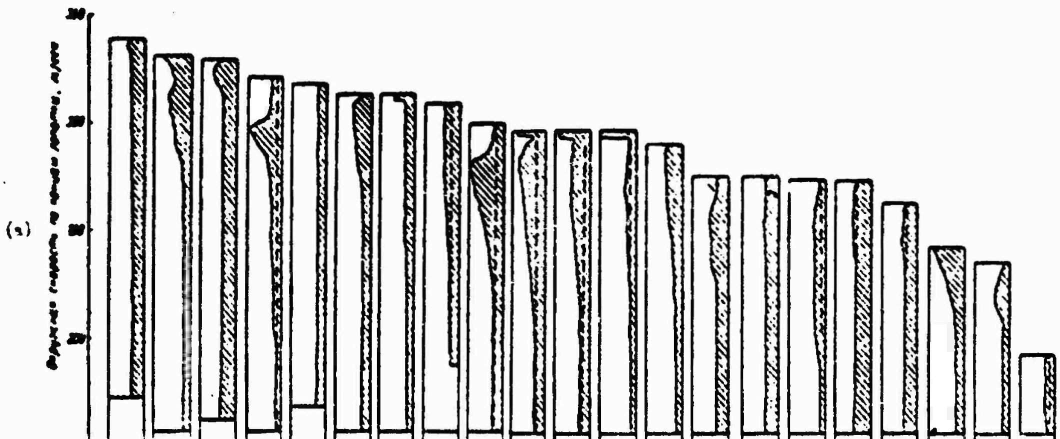
The strongest erosive influence is produced by large drops of condensate, since they are more difficult to accelerate by vapor flow, i.e., their absolute velocity $c_ж$ is less, and relative velocity $w_ж$ and its normal component $w_{ж.n}$ are more than for small drops. Consequently, force of the impact of a separate drop with increase of its dimension will grow faster than the mass of a drop.

The question of the actual diameter of droplets causing the erosion of blades of steam turbines is still insufficiently investigated. Inasmuch as in many turbines the axial clearance between nozzle boxes and rotor blades is small, it is quite possible that disintegration of drops is not completed and drops reaching blades of rotor have a diameter exceeding that which corresponds to critical value

[1]In examining turbines working on water vapor we talk about that region of conditions in which growth of velocity of a drop in absolute motion $c_ж$ leads to deceleration of drop with respect to blades $w_ж$.

of Weber number. With increase of axial clearance, along with improvement of conditions of splitting drops into smaller ones absolute velocity of drops $c_{ж}$ and relative $w_{ж}$ velocity of drops decreases; number of drops separated on the housing also increases. Therefore, sometimes even a comparatively small increase of axial clearance can lead to a substantial decrease of erosion damage of blades.

Pohl's collected mappings [3] of erosion wear of blades of the last stages of impulse-type and reactive turbines are presented in Fig. 16. The leading edges of blades are depicted while the positioning of blades along the axis of ordinates is such that the upper end of the blade shows peripheral velocity. Under the figure the table gives data on maximum and mean values of moisture, number of hours of operation, material of blades and type of stage (reactive "P" or active "A"). From analysis of data shown in Fig. 16 it is not possible to establish that blades working with increased peripheral velocity or blades working in high vapor moisture are always subject to large wear. Consequently neither level of peripheral velocities nor vapor moisture by itself determines erosion. Erosion is determined by the complex influences of the above factors.



(b)	348	332	330	32[illegible]	319	310	310	309	30[illegible]	294	294	294	283	275	275	275	275	262	242	235	196
(c)	11	10-12	10	9.5-10	8.5	8.5	8.5	8.5	8-9	9.5-10	10	10-12	9-9.5	8.5	10	12.5	8.5	8.5	7.5-8.5	7.5-8	8.5
(d)	[illegible]	2400	-	11000	30000	8500	14800	28000	3500	[illegible]	13000	3500	13300	[illegible]	11000	4000	5500	12000	3000	4000	30000
(e)	A	P	A	P	A	A	A	A	P	P	P	P	A	P	P	P	P	P	P	A	E
(f)	5%Ni	VSM	VSM	VSM	5%Ni	5%Ni	5%Ni	5%Ni	5%Ni	5%Ni	5%Ni	5%Ni	5%Ni	5%Ni	VIM	5%Ni	5%Ni	5%Ni	5%Ni	5%Ni	5%Ni
(g)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21

Fig. 16. Diagrams of erosion wear of leading edges of blades of last stages of impulse-type and reactive steam turbines.
KEY: (a) Peripheral velocity along blade ends; (b) Peripheral velocity m/s; (c) Vapor moisture, %; (d) Number of hours of operation; (e) Active stage A, Reactive stage R; (f) Blade material; (g) Number, in order.

Increased wear of peripheral parts of blades of rotors (as compared to root parts) which is observed in a number of cases (see, for instance blade No. 2, 4, 9,

and others, in Fig. 16), it is possible to explain: a) by increased peripheral velocities at ends of blades; b) by thrusting of water from root to periphery of blades, creating increased humidity in peripheral streams; c) by secondary eddies near the housing, promoting ejection of condensate from the liquid film covering the housing and collision of drops on peripheral sections of blades of rotor.

Group of researchers [3, 4, 41, 122 and others] notes increased wear of blades in the trace from the stands, sharp breaks of flow-through part (Fig. 17) and other elements. This is explained by accumulation and subsequent removal of condensate from boundary layer of these elements.

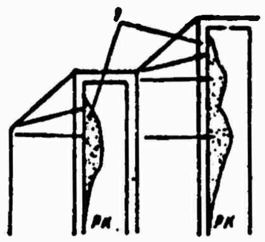


Fig. 17. Zones of erosion wear of rotors (1) opposite sharp breaks of the flow through part.

5. Design of Steam Turbine Blades Against Erosion

A universally recognized fully reliable method of designing turbine blades against erosion as yet does not exist. In works published in recent years this question has not been considered. However in prewar years the Soviet researcher L. I. Dekhtyarev started an attempt to create such a method of design[1] [1 and 2]. Results obtained by L. I. Dekhtyarev present a definite interest even at the present.

The method of design proposed by L. I. Dekhtyarev leads to calculation of conditional stress from the impact of droplets in the surface layer of the blade material and to showing a limited period of service depending upon the magnitude of the stress. The dependence between conditional stress and period of service was determined on the basis of treatment of statistical data on turbines in operation in that period. Below is a brief account of the method of L. I. Dekhtyarev.

Considering the impact of a droplet against the blade as a blow of an absolutely nonelastic sphere, it is possible to record the expression for power impulse P of blow

$$P\Delta t = mw_{н.а.} \qquad (8)$$

[1]L. I. Dekhtyarev perished during the Second World War and his work has remained uncompleted.

where $w_{ж.n}$ – normal component of relative speed of droplet (Fig. 15);

m – mass of droplet;

Δt – time of action of force, which is determined assuming that path of shift of center of gravity of droplet during the time of the impact is equal to initial radius of droplet (d/2).

For determination of pressure p, acting on surface blade upon impact of a droplet, force P belongs to area of middle of droplet

$$p=\frac{P}{F_{мид}}. \tag{9}$$

The last expression after simple conversions acquires the form

$$p=\frac{2}{3}\frac{\gamma_{ж}}{g}w^{2}_{ж.n}. \tag{10}$$

Introducing a series of simplifying assumptions L. I. Dekhtyarev obtained a formula for determination of absolute velocity of drop in front of the rotor[1] $c_{ж}$. And then using this formula and trigonometric relationships for velocity triangles, he converted expression (10) to a form convenient for calculation of conditional magnitude of pressure from the impact near the tip of the blade where force of impact is maximum:

$$p=0{,}68\cdot10^{-6}u^{2}_{макс}\sin^{2}\beta_{1пер}\left(1-2{,}42\frac{\mu_{п}\gamma_{п}}{\sigma}c^{2}_{п}\sqrt{\frac{S}{\sigma\gamma_{ж}}}\right). \tag{11}$$

where $u_{макс}$ – peripheral velocity for tip of rotor, m/s;

$\beta_{1пер}$ – angle of incidence on tip of rotor blade (Fig. 15);

$\mu_{п}$ – coefficient of viscosity of vapor, $kgf\cdot s/m^2$;

σ – surface tension of water, kgf/m;

$\gamma_{п}$ – specific gravity of vapor before entrance into rotor, kg/m^2;

$c_{п}$ – absolute velocity of vapor on leaving nozzle box, m/s;

S – axial clearance between blades of nozzle box and rotor, m;

$\gamma_{ж}$ – specific gravity of water, kg/m^3.

The period of service of blades depending upon stress found by formula (11) for the usual nickel and stainless steels according to L. I. Dekhtyarev is determined in Table 1.

The value of the method proposed by L. I. Dekhtyarev is first of all the clear representation with which in formula (11) the influence of different parameters on erosion resistance is shown. What was said in § 4 as regards influence on

[1]We remind the reader that at present there are stricter methods for determining the speed of a drop in vapor flow (see, for example, [33]).

erosion from peripheral velocity u, angle of incidence into rotor β_1, density and absolute velocity of vapor on exit from nozzle box c_{Π}, axial clearance between nozzle box and rotor S directly follows from formula (11).

Table 1

Stress, found by formula (11) kgf/cm^2	Tentative period of operation of blades, h
To 250	Erosion practically not observed
From 300 to 350	Over 50,000
From 400 to 450	Near 50,000
From 500 to 600	15,000-25,000
From 650 to 700	500-10,000
Over 700	Near 3,000

As can be seen from what has been presented, L. I. Dekhtyarev's basis of design of turbines against erosion is simplified presentations about liquid-drop impact. He does not delve into the fine points of the mechanism of erosion damage under liquid-drop impact, which will be considered in Chapter 3. However, exponential dependence of the destructive factor on collision rate obtained by him will agree with contemporary presentations and experimental data on erosion.[1]

We note that determination of period of service on the basis of Table 1, proposed by L. I. Dekhtyarev, is possible only for turbines working on steam and with blades from specific materials. However this does not lower the value of formula (11) for comparative evaluations of erosion resistance of turbines of other types working in similar conditions (identical working substance, identical temperatures and materials of blades, etc.).

A deficiency of formula (11) is that it does not consider diameter of drops striking the blade.

[1]The destructive factor during calculation of erosion by the method of L. I. Dekhtyarev should be considered a conditional magnitude of pressure during impact of drops against surface of blade.

C H A P T E R   T W O

EROSION RESISTANCE OF MATERIALS

6. Methods of Experimental Investigation of Erosion Resistance of Materials

Investigation of erosion resistance of materials until recently was done only by experimental means, while the most reliable data were obtained during investigatior of materials in natural conditions. In reference to blades of steam turbines, natural tests were conducted even in the thirties [42]. However the organization of such an experiment is very difficult. Therefore frequently laboratory methods are used, which are very effective during determination of comparative erosion resistance of different materials. Below are brief characteristics of laboratory methods of investigations.

1. Impact of stream against revolving sample. Sample is fastened on periphery of revolving disk, at every turn intersects a stream of water or moist vapor perpendicular (Fig. 18). Periodic collisions of a stream of water against a sample simulate impacts of drops of a condensate. Experimental installations of such kind are called shock stands. Results of shock stand tests are presented usually in the form of dependences of loss of weight or volume of sample on number of collisions of a stream against the sample or on duration of test.

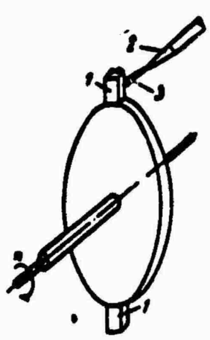


Fig. 18. Diagram of stand. 1 – samples; 2 – nozzle; 3 – stream of water or vapor.

Tests on such an installation are very frequently conducted at low peripheral velocities of rotation of samples and when diameter of stream of water is 5-10 mm (see,

for instance [43 and 44] tests were conducted at u = 78 m/s in [3], results of tests up to u = 225 m/s are given). Recently a short report appeared [45] about an installation with double rotation made for investigation of erosion at high peripheral velocities, and allowing tests at collision velocities of drops with samples exceeding 600 m/s.

2. Impact of stream or drops of liquid (vapor) against motionless samples. The diagram of one installation similar to that used by Czechoslovakian researchers [46] is represented on Fig. 19. This method usually is applied during investigations of destructive action of a stream at high-speed collisions (for example in [47] results are given of tests at speeds of a stream up to 600 m/s, and in [48] to 1,050 m/s).

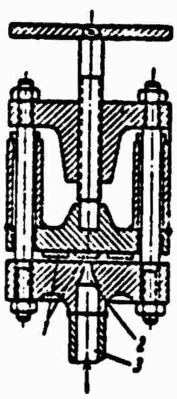


Fig. 19. Diagram of installation for investigation of erosion by collision of a stream of moist vapor against a sample. 1 – tested sample; 2 – nozzle; 3 – steam pipe.

3. Tests of erosion resistance of materials in the presence of a flowing liquid with cavitation near surface of sample. For this purpose cavitation nozzles or slot installations with a narrow slot are used. Figure 20 shows the diagram of one possible construction of a cavitation nozzle [43]. Area of the narrowest cross section of nozzle in which appear cavitation bubbles is regulated by screw 1. Near sample 2 bubbles collapse, causing damage of its surface. Throttle device 3 serves for adjustment of counterpressure in nozzle. This method of investigations erosion damage is simple but requires lengthy testing.

4. Investigation of erosion resistance of materials on magnetrostrictive vibrator (Fig. 21). The essence of this method is placing the test sample on the end of a nickel rod or tube immersed in working fluid, and accomplishing longitudinal oscillations with frequency 7,000-20,000 Hz and amplitude of several tens of microns. The rod (or tube) oscillates under the influence of an alternating magnetic field created by a field coil. Oscillations appear because rods from certain materials (in particular from nickel) have the property of changing length under the influence of an alternating magnetic field

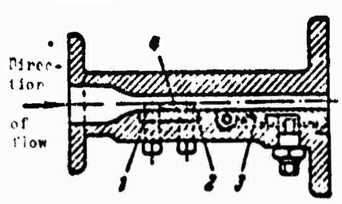


Fig. 20. Diagram of cavitation nozzle. 1 – control screw; 2 – sample; 3 – throttle; 4 – zone of cavitation.

phenomenon of magnetostriction). The test sample oscillates together with the rod. At every rise rarefaction appears accompanied by formation of cavitation bubbles at the surface of the sample which in following instant are destroyed under action of the approaching sample.

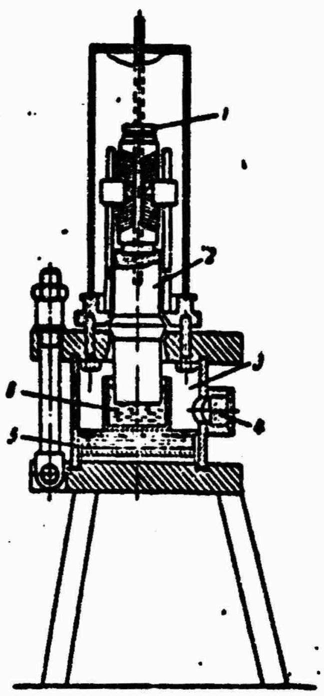


Fig. 21. Diagram of magnetostrictive instrument. 1 – nickel packet; 2 – connecting rod; 3 – boiler; 4 – viewing window; 5 – heating elements; 6 – liquid.

Test of erosion resistance of materials on magnetostrictive instrument is attractive because of the speed and possibility of conducting investigation at different temperatures of working fluid. Duration of test of every sample usually is limited to two-three hours and erosion resistance of material is characterized by loss of weight of sample after a specific testing time. The test requires several tens of cc working fluid. Power expended by instrument is less than 1 kW [49 and 50].

5. <u>Investigation of erosion resistance of materials on motionless samples with a ring exciter of oscillations</u> (Fig. 22). The installation consists of a cylindrical glass filled with water with a ring from barium titanide placed below the water level. When an alternating electric field is applied to the surface of the ring, the volume of the ring starts to oscillate with the frequency of the field. Upon appropriate selection of frequency of field and geometric dimensions of installation standing waves are formed in the liquid which give a large amplitude of oscillation of pressure near the center slabs where the sample is attached. On the surface of sample cavitation appears. In this relatively recently developed [51 and 52] method of reproduction of erosion damage in laboratory conditions no acceleration is applied to the sample in contrast to the usual magnetostriction instrument in which the test sample vibrates. Damage is sufficiently rapid and time of test, depending upon form of material, changes from a few minutes to 2-3 hours. Evaluation of resistance of material is made according to magnitude of loss of weight of samples after a specific time.

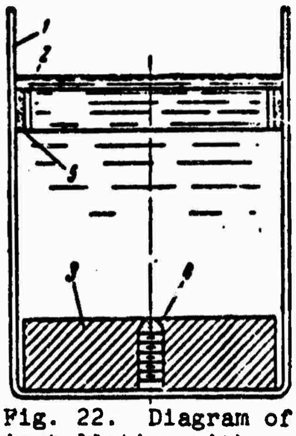


Fig. 22. Diagram of installation with ring-type oscillation exciter. 1 – glass; 2 – ring from $BaTiO_3$; 3 – plate; 4 – sample; 5 – rubber.

From this brief description one may see that if in the first two methods of test erosion damage of samples occurs directly from the impact of a stream or drops into which the stream disintegrates, i.e., conditions of damage directly model conditions of damage of turbine blades from the impact of drops, then this cannot be said of the last three methods. Therefore it is necessary to know in what connection results of tests of erosion resistance of materials by different methods are found, and, in particular, whether different methods of test give identical comparative appraisal of erosion resistance of different materials; whether a series of materials located in order of growth of their erosion resistance by results of tests, for instance, on an erosion-shock stand can be supplemented by another series according to results of tests on a magnetostrictive instrument, if certain materials are tested by one or another method. The answer to these questions can be obtained by comparing results of different tests.

A group of researchers has studied such comparisons. Thus for instance, de Haller [53] and then Mousson [54], as a result of comparative investigation of a large group of metals on shock stand, i.e., during multiple impacts against a stream of water and in a cavitation nozzle, came to the conclusion that in both methods of tests the investigated materials go identical sequence with respect to erosion resistance. The same was reached by Kerr [55] as a result of comparison of results of tests on a magnetostrictive vibrator and in a diffuser. L. A. Glikman and E. M. Raykhel'son [43 and 56] report an analogous result of comparison of erosion resistance of a large number of different steels, cast iron, brasses and bronzes with respect to results of tests of these materials on a shock stand and a magnetostrictive vibrator. An analogous picture can be obtained if we compare results in [52] of erosion resistance of several metals on an instrument with ring-type oscillation exciter with results of tests of the same materials by other methods. Thus, it is possible to consider fixed the rule according to which materials with respect to erosion resistance are in practically

the same sequence independently of the method of tests.[1] This is explained by the generality of the nature of erosion damage under impacts of drops of liquid and during cavitation in a liquid medium (see Chapter 3).

It is necessary to stress that intensity with which erosion damage occurs during tests by different methods is different. Up to now a universal method or criterion which would allow a simple quantitative appraisal of intensity of erosion independently of method of tests has not been found. In spite of this, the established fact of identical distribution of materials with respect to cavitation and erosion resistance independently of method of investigation is very important inasmuch as it expands the methodological possibilities of study of erosion resistance. Relying on them, it is possible to choose the method of tests most convenient and simple for a given situation.

7. Results of Experimental Investigation

a) Influence of Parameters of Steam on Erosion Wear

The method of investigation of erosion resistance which is very wide-spread is the impact of a stream against the sample. Tests by this method were conducted long ago (see [22, 53, and 58]). Systematized data are contained in the article of Pohl [3]. In these experiments the sample was fastened to a revolving disk and at every turn was subjected to the influence of a stream of water directed at a right angle to the plane of rotation (Fig. 18). It is clear that phenomena occurring upon impact of drops and stream of water are impossible to identify, i.e., from these experiments it is impossible to find numerical ratios determining erosion of real turbine blade. However comparison of results of these tests in order to determine influence of separate factors on erosion, other things being equal, is fully permissible. In Fig. 23 is presented dependence of loss of weight of sample on number of impacts and peripheral velocity. From the figure one may see that for the beginning of erosion wear of material a rather large number of impacts is required. This number of impacts is determined by the peripheral velocity

[1] We note that there can be exception to this rule [57]. The comparison of test results on resistance to cavitation erosion by the impact of a stream and magnetostrictive method shows for certain materials a difference which is greater the less the density and uniformity of the material.

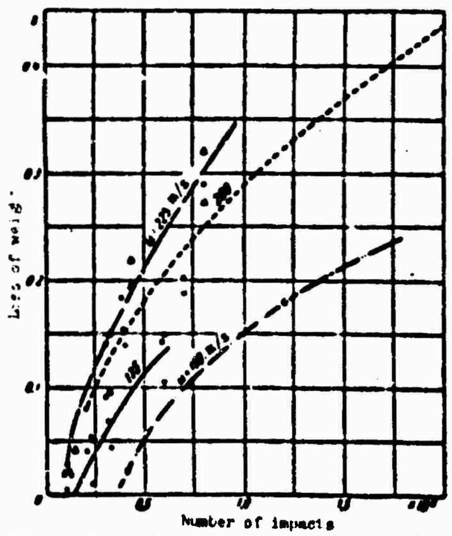


Fig. 23. Dependence of erosion wear on number of impacts and peripheral velocity of rotation of samples (diameter of stream is 1.5 mm).

of rotation of the sample, while for a stream with diameter 1.5 mm and at peripheral velocities of 125 m/s and lower, loss of weight of samples was not fixed. Analysis of curves shown in Fig. 23 shows that there exists an exponential (almost quadratic) dependence of wear on peripheral velocity of rotation of sample, or, in other words, on velocity of collision of stream with sample (in described experiments speed of water flow from nozzle as compared to peripheral velocity of rotation of sample can be disregarded).

A. D. Moiseyev [59], generalizing experimental data about influence of rate of water flow on rate of surface damage of steel both in shock conditions and slot erosion confirmed that there exists an exponential dependence, where the exponent $n > 1$. V. G. Zelenskiy [60] on the basis of experimental investigation of erosion under water flow in a slot found that wear is proportional approximately to the cube of flow rate in the slot.

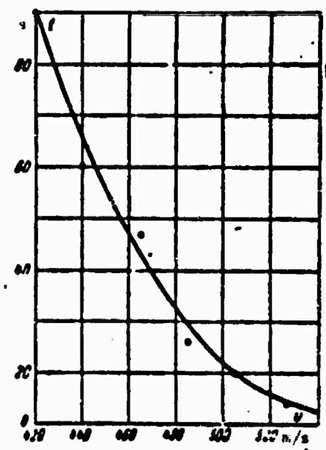


Fig. 24. Dependence of time of puncture of a plate from duralumin on exhaust velocity of water.

Experiments conducted under high stream velocities show sharper erosion wear with increase of stream velocity. In this relation, results given in [47] of a test on the piercing of motionless plates upon impact by a stream of water with velocity 400-600 m/s are interesting. Dependence of time of puncture t of a duralumin plate 3 mm thick on exhaust velocity of stream v from nozzles 0.84 mm in diameter is represented on Fig. 24. In the investigated velocity range (420-550 m/s) the erosion rate (inverse of puncture time) is approximately proportional to velocity of stream in the 8th stage.

Thus different researchers agree that there exists an exponential dependence of erosion wear on speed of collision with component but they give the index

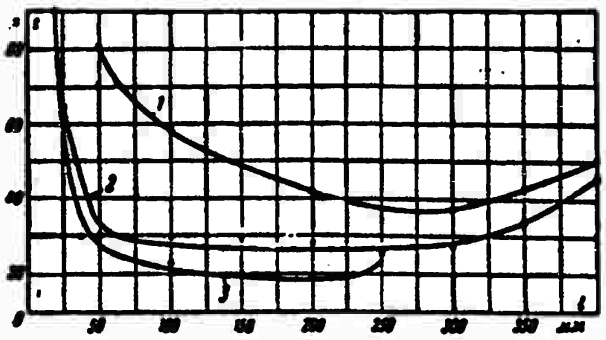


Fig. 25. Dependence of puncture time of a plate by a stream of water on distance between nozzle and plate and on nozzle diameter; stream velocity 440 m/s nozzle diameter: 1 – 0.84 mm; 2 – 0.74 mm; 3 – 0.64 mm.

different values and it is doubtful whether this is possible to explain by inaccuracies of experiment. Most likely this is connected with different conditions of experiments.

There is also not one opinion on the relationship of the influence of the stream diameter on erosion wear. For instance, analyzing results of tests on an erosion shock stand, Pohl [3] arrives at the conclusion that erosion wear is increased approximately in proportion to the square of stream diameter. However, during later investigations of puncture time of motionless plates by a high-speed stream [47] it is found that with decrease of stream diameter its effectiveness increases (Fig. 25). From the figure one may see also that when the nozzle is taken a certain distance from the plate the same effect is obtained as with decrease of diameter. The authors of the article [47] explain this phenomenon by the fact that with decrease of stream diameter and when the nozzle is removed from the plate the stream is more strongly sprayed and the impacts blows of separate drops against the metal surface destroy it more effectively than the impact of a solid stream.

Comparison of results of experiments [3 and 47] shows that increase of speed of collision of stream with sample from 150-220 to 400-600 m/s produces very significant changes in character of erosion influence of stream on part.

b) Dependence of Erosion Resistance on State and Properties of Surface of Part

Many researchers tried to find the dependence of erosion resistance of materials on their mechanical qualities (time resistance, viscosity, fatigue limit, relation of yield point to ultimate strength, surface hardness, etc.). Of works in which this question is discussed it is possible to note [43 and 61-66]. It has not been possible to establish general dependences; however it has been noticed that with increase of surface hardness, other things being equal, erosion resistance of metals as a rule grows [43, 63, 64 and others]. This may be distinctly seen

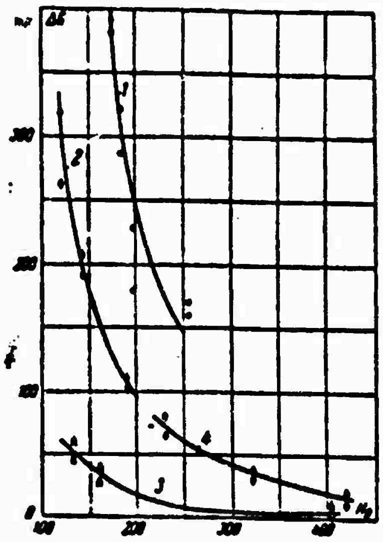


Fig. 26. Influence of hardness on erosion resistance of different materials (ΔG – loss of weight of sample after 3 h of test). 1 – cast iron; 2 – carbon steel; 3 – austenitic steel; 4 – stainless steel of brand 1Kh13 under different heat treatment.

from Fig. 26 where dependences from [43] of erosion resistance of different groups of materials on their hardness are represented, obtained during tests on a magnetostrictive apparatus.

Comparison of erosion resistance of cast iron and steels having identical hardness shows that cast irons have less erosion resistance than steel. The latter is because cast irons contain easily destroyed microscopic inclusions of graphite. As investigation of the character of the damage showed, erosion damage begins from the time these fragile structural components are chipped. Austenitic steels resist erosion better than the usual carbon steels of the same hardness. Keller [64] obtained analogous data, comparing results of tests different materials on an erosion-shock stand. In experiment of Keller it was also shown that erosion resistance of hard copper alloys (in particular bronzes containing Al, Fe, Mn and Ni) is greater than for steels of the same hardness.

In a number of works results of the investigation of erosion resistance are reported for different artificially created coatings and various methods treatment of a metal surface. For instance the investigation on an erosion-shock stand and magnetostrictive vibrator of electrolytic chrome plating of different steels whose Brinell hardness was from 160 to 250 is reported in [43]. It was established that erosion resistance of this coating essentially depends on thickness of layer of chromium, conditions of chrome plating and subsequent treatment of part (for example, on temperature of annealing). When the layer of chrome is thicker than 0.04 mm and there are appropriate selected technological conditions, chrome plating can noticeably increase erosion resistance of part.

Surface hardening of a number of brands of steel can be achieved as is known, with nitration. However, with respect to influence of nitration of surface of part on its erosion resistance under the shock influence of a stream of water and during cavitation, there does not exist one single opinion. Some, based on

experiments, consider surface nitration not effective [2, 46 and 67] and others [43 and 68] present experimental data indicating that erosion resistance of nitrated steels after nitration is increased many times. It is interesting to note that authors of [67 and 68] coming to directly opposite conclusions with respect to influence of nitration on erosion resistance of material investigated the same brand of steel — [38KhMYuA] (38XMЮA]. Success or failure of this method of increase of erosion resistance depends apparently on selection of rational technology and on expediency and thoroughness of subsequent treatment of surface after nitration (see [68]).

Shot-blasting treatment of the surface of carbon and austenitic steels of brand [1Kh18N9T] (1X18H9T) according to the date of Glikman [43] almost does not increase erosion resistance.

During tests it was established that with increase of frequency of surface treatment erosion resistance is increased. For instance, polished samples wear out much less than unpolished samples. It is necessary to mention also results of experiments of Vater [61] which showed that even an inconspicuous porosity of material (microporosity) noticeably worsens its erosion resistance.

c) Results of Investigation of Erosion Resistance of Different Materials

In the last three decades many articles have been published in which results of experimental investigations of erosion resistance of different materials by various methods [42-74 and others]. Erosion resistance was investigated for metals intended for manufacture of blades of steam turbines, component of hydraulic turbines, ship screw propellers, parts with sealing surfaces, high pressure locks, various hard alloys of nonmetallic materials, etc.

Classical data on resistance to erosion wear of a number of brands of steel for manufacture of steam turbines blades (Fig. 27) were obtained during tests of natural turbines with groups of blades from different materials by the Berlin Union of electrical stations [42]. This graph appeared in a number of journalistic articles and books published in various countries [4, 6, 20, and others]. As the graph shows, of the investigated metals the best anti-erosion qualities belong to chrome-nickel-tungsten steel WF-100 and manganese unabraded steel containing around 13% manganese.

Analogous results were obtained from the Brown-Boveri [74 and 2] firm during

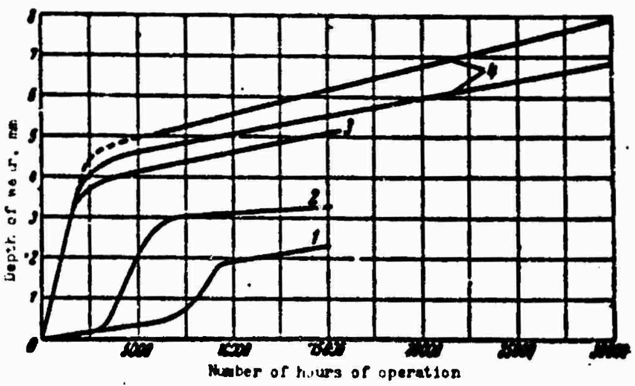


Fig. 27. Dependence of erosional damage of blades on number of hours of turbine operation. 1 – manganese steel; 2 – WF-100 composition: 0.45% C 0.39% Si, 0.3% Mn, 15.4% Cr, 11.7% Ni, 0.27% Mo, 1.97% W; 3 – Monel-metal composition: 67% Ni, 28% Cu, 5% Fe + Mn; 4 – V5M composition: 0.7% Ni, 14% Cr, 0.5% Mn, 0.16% C, 0.6% Si, 0.02% S, 0.08% P.

tests of a 36,000 kW turbine at $n = 3000$ r/min, $p_1 = 31$ at and $t_1 = 425°C$ on the last stage of which were groups of blades from 15 different brands of steel with 7-8 blades in every group. Chemical composition of the steel is given in Table 2 and results of tests in Fig. 28. As can be seen from this table and the graph the usual stainless steels possess approximately identical erosion resistance. The best are steels with a high chromium and nickel content (steel No. 12) and chrome-nickel tungsten WF-100. The most erosion resistant, according to data of the firm BBC, turned out to be blades of steel No. 6 with tempered edges.

Table 2

No. sample	Name of steel	Chemical composition, %							Time resistance to rupture kgf/mm^2
		C	Si	Mn	Cr	Ni	Mo	W	
1	5% Ni	0.20	0.35	0.50	–	5.06	–	–	76
2	5% Ni; nickel-plated	0.20	0.35	0.50	–	5.06	–	–	76
3	5% Ni; chrome-plated	0.20	0.35	0.50	–	5.06	–	–	76
4	Rust-resistant chrome-steel	0.08	1.04	0.40	12.0	0.17	–	–	74
5	The same	0.27	1.20	0.17	14.0	–	–	–	72
6	Rust-resistant chrome-steel tempered	0.27	1.20	0.17	14.0	–	–	–	(140)
7	Rust-resistant chrome-steel	0.08	0.23	0.61	15.97	–	–	–	79
8	The same	0.24	0.56	0.43	15.40	0.66	–	–	68
9	The same	0.40	1.15	0.40	15.60	0.60	–	–	69
10	The same	0.22	0.30	0.37	16.60	0.06	–	–	80
11	Rust-resistant chrome-nickel-tungsten steel	0.45	1.39	0.30	15.43	11.70	0.27	1.97	80
12	Rust-resistant chrome-nickel steel	0.07	0.89	0.66	21.1	11.90	0.57	–	75

(Table 2 Cont'd)

No. sample	Name of steel	Chemical composition, %							Time resistance to rupture kgf/mm^2
		C	Si	Mn	Cr	Ni	Mo	W	
13	The same	0.40	0.34	1.99	11.5	34.7	0.20	–	82
14	The same	0.30	0.22	0.74	9.17	37.8	0.20	–	73
15	Molybdenum chrome-plated	0.40	0.20	0.66	–	–	0.27	–	67

The character of curves in Figs. 27 and 28 testifies to presence of two stages of erosion wear, where on the first stage damage of material is considerably faster than on the second. The slowing of erosion on the second stage in certain works (for instance in [4]) is explained by the protective action of the layer of water which is held on the surface of blades by the erosion pits formed earlier and also by the increase of axial clearance between nozzle box and leading edges of blades.

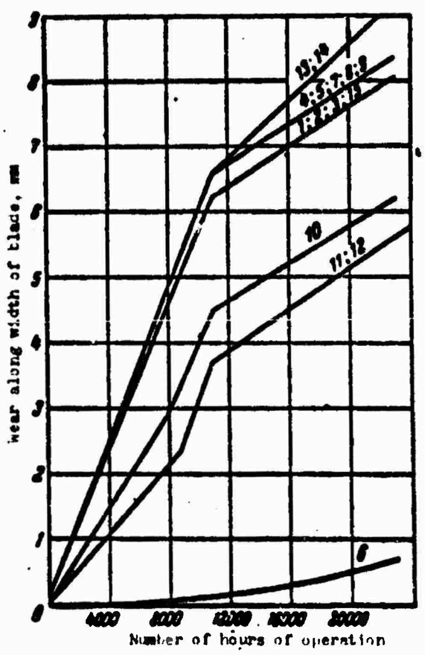


Fig. 28. Dependence of erosion damage of blades made of various materials on number hours of turbine operation; designations of curves correspond to numbers in Table 2.

Investigations of erosion resistance of different materials have been conducted in the postwar years on laboratory installations of various types. For instance in the previously mentioned book of L. A. Glikman [43] results were given of tests of a broad class of metallic and nonmetallic materials on a magnetostrictive vibrator and on an erosion shock stand. In Fig 29 taken from [43] results of tests of erosion resistance of a number of brands of steel on a magnetostrictive vibrator[1] are represented. Among these steels is stainless steel [1Kh13] (1X13), used for manufacture of blades of steam turbines. Investigated samples of steel 1Kh13 were tempered with t = 1050°C and annealed at t = 700°C.

[1]Analogous data for the same materials are obtained also from tests on an erosion-shock stand.

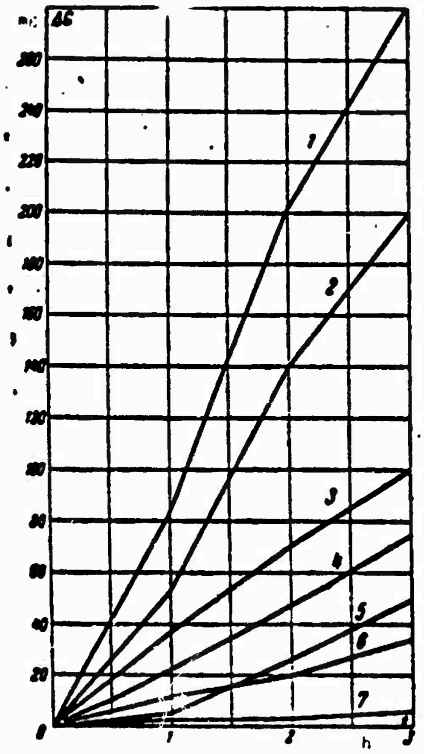


Fig. 29. Loss of weight of samples depending upon time of test. 1 – carbon steel (C = 0.15%); 2 – carbon steel (C = 0.31%); 3 – carbon steel (C = 0.56%); 4 – stainless steel 1Kh13; 5 – austenitic steel [1Kh18H9T] (1X18H9T); 6 – austentic steel 18-8; 7 – austenitic steel [EI-388] (ЭИ-388).

From Fig. 28 one may see that steel 1Kh13 after heat treatment approaches carbon steel of the same hardness in erosion resistance. If, however, after tempering a lower temperature of annealing is applied, it is possible to attain an increase of hardness and erosion resistance of this steel by a few times (see curve 4 in Fig. 26; three groups of points on this curve correspond to annealing temperatures of 700, 550 and 500°C). However, it is necessary to note that increase of erosion resistance of material in such a way is limited by the impairment of plasticity and viscosity of material. In this connection L. A. Glikman [43] talks about advisability of application of local or surface hardening for increase of erosion resistance of parts.

In recent years, both in our country, and also abroad work has been conducted on introduction of alloys on a titanium base for manufacture of steam turbine blades [72, 75, and others]. Alloys whose basic components are titanium and aluminum have significantly lower specific gravity and significantly greater specific strengths[1] than stainless steels used for manufacture of steam turbine blades. Therefore, replacement of stainless steel by titanium alloys would allow an increase of blade length of the last stages, preserving high values of peripheral velocities at ends of blades, i.e., remove one barrier to further improvement of contemporary steam turbines.

A study has been conducted of properties of a number of stable alloys of titanium to determine the possibility of using these alloys for blades of steam and gas turbines designed for protracted exploitation. It was found that many of the investigated alloys of titanium up to a temperature of 450°C possess higher

[1]Specific strength is defined as the ratio of permissible stress to specific gravity of material.

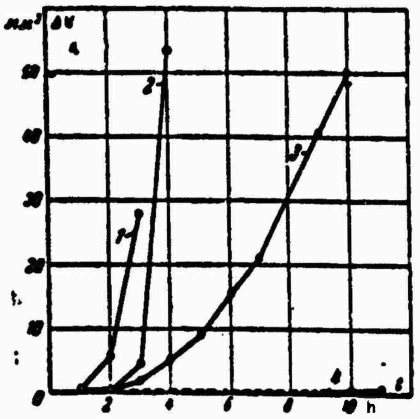


Fig. 30. Decrease of volume of samples depending upon time of tests on erosion-shock stand at a peripheral velocity of rotation of samples of 78 m/s. 1 – titanium; 2 – steel 2Kh13; 3 – aluminum alloy of titanium; 4 – cobalt satellite.

values of short-term strength, rupture strength, creep resistance, fatigue limit and erosion resistance but smaller plasticity than stainless steel of brand 2Kh13. As a result of investigation, for semiindustrial testing as material for manufacture of blades of the last stages of steam turbines with temperature to 100°C an alloy of titanium with aluminum is recommended.

In [72] are given results of comparative investigation of erosion resistance of cobalt stellite an aluminum alloy of titanium, steel (brand 2Kh13) and technical titanium an erosion-shock stand and on a magnetostrictive installation. These results are reproduced in Table 3 and in Fig. 30. Consideration of these data permits concluding that commercial titanium has low resistance to erosion damage. Erosion resistance of the investigated aluminum alloy of titanium is higher than for stainless steel 2Kh13 but significantly lower than for cobalt stellite.

Table 3. Results of Tests on Magnetostrictive Installation with Frequency of Oscillations 20 kHz and Amplitude 0.025 mm

Material	Hardness H_B	Losses over 3 h of testing	
		mg	mm^2
Commercial titanium........	170	36.5	8.1
Steel 2Kh13.......	207	57.5	7.4
Alloy of titanium with aluminum...	270	14.1	3.2
Stellite..........	360	1.8	0.22

Wide industrial introduction of titanium alloys for manufacture of blades of powerful steam turbines still apparently awaits much work. For instance in [75] it is shown that the Parsons firm could not reach positive results in developing techniques of fastening protective stellite cover plates on titanium blades. Overlaying welding from other hard alloys turned out to be ineffective.

At the Prague Power Institute and Prague Scientific Research Institute of Materials and Technology investigations were conducted of the erosion resistance

Table 4

Designation of alloy	Chemical composition, %									Hardness kg/mm^2	Loss of weight after 336 h, mg
	C	Mn	Si	Cr	Co	W	Ni	V	Fe		
Stellite No. 1..........	2.67	0.33	0.62	27.49	48.84	17.33	—	—	2.08	702	88.5
Stellite No. 12..........	1.90	0.27	0.68	26.01	57.08	11.04	—	—	2.36	571	5.1
Stellite No. 6..........	1.03	0.27	0.71	26.13	65.22	4.08	—	—	2.57	408	4.6
A-25Co..................	2.33	—	0.30	27.28	32.80	15.15	—	—	20.14	581	1.4
A-15Co..................	2.62	—	0.23	29.69	33.68	12.25	—	—	20.14	543	2.0
B-25Co..................	2.80	—	0.66	28.17	10.36	13.12	—	—	43.12	588	4.6
B-15Co..................	2.32	-	1.12	31.17	11.21	4.32	—	—	49.77	486	1.7
A-2-15Co................	1.23	0.12	0.49	27.51	34.51	5.77	—	—	32.25	449	3.9
B-2-25Co................	1.82	0.03	0.40	27.17	12.91	4.74	—	—	54.67	482	2.6
No. 1...................	1.68	0.49	0.63	16.55	—	24.00	58.10	0.44	Remainder	364	29.5
No. 2...................	1.68	0.50	0.82	14.67	—	20.10	58.20	2.36	The same	351	229.2
Chakov II...............	3.12	0.29	0.58	29.98	—	—	—	—	The same	633	2.0
Sormite No. 1...........	3.16	1.74	3.00	30.39	—	—	3.20	—	The same	550	1.0
Sormite No. 2...........	1.97	0.52	—	15.44	—	—	2.44	1.36	The same	365	1.5
25Ni12..................	2.72	0.29	0.51	26.05	—	—	14.73	1.46	52.06	373	1.7

of fifteen types of alloys intended for work at high temperatures, including several brands of stellites (nonferrous alloys on a cobalt-chromium-tungsten base) and alloys of substitutes with decreased content of deficient cobalt or without any cobalt [46]. Tests of all samples were conducted for two weeks in moist vapor which through a nozzle d = 2 mm with calculated velocity 270 m/s on tested sample. A diagram of the installation is shown in Fig. 19. Chemical composition of the sample material and results of tests are given in Table 4. Loss of weight was defined as the average magnitude for results of tests of nine identical samples. From Table 4 one may see that of the alloys of stellite type with minimum content of iron hypoeutectic stellite No. 6 is worn least, whereas stellite No. 1 has low resistance to erosion by moist vapor. With increase of iron content in such alloys, their erosion resistance is increased (materials A-25Co; A-15Co; Б-25Co). It is necessary to note especially that all varieties of alloys with lowered cobalt content and also sormite Nos. 1, 2 and Chakov-II showed higher stability against erosion wear by moist vapor than the best of the high-alloy cobalt stellites, i.e., stellite No. 6 with 65% cobalt.

Data on comparative erosion resistance of tungsten, molybdenum, several forms of titanium alloys and other materials coming into use are given in [52]. Experiments were conducted on motionless samples placed in a vessel with a ring-type oscillation exciter (Fig. 22). Results of tests are represented in Table 5 from consideration of which it follows that of the number of investigated materials the greatest erosion resistance is possessed by titanium alloy 150-A and tungsten. Investigation of tested samples shows that materials with ultimate strength of the order 35 kgf/mm^2 (nickel, brass, pure titanium) are plastically deformed almost immediately after beginning of tests. Consequently, stresses appearing in the surface layer of the sample material during cavitation must be not less than this magnitude. On the other hand, inasmuch as damage of such materials as tungsten and titanium alloy 150-A with ultimate strength 100 kgf/mm^2 and above occurs very slowly, cavitation stresses in the surface layer are apparently lower than this magnitude.

Interesting data about damage of metallic plates by a high-speed stream of water are given in the above article [47]. Plates 1.5 mm thick were placed perpendicularly to axis of stream at 50 mm from a nozzle 1 mm in diameter.

Table 5

Name of material	Brinell hardness, H_B	Ultimate strength on rupture, kgf/mm^2	Elastic modulus kgf/mm^2	Depth of damage in sample, μ					
				after 1 min	after 15 min	after 30 min	after 1 h	after 2 h	after 3 h
Aluminum (soft)....	16	11.2	7,000	80	—	—	—	—	—
Titanium (annealed)	58	55.3	11,200	—	43	78	—	—	—
Nickel............	90	35.0	21,000	—	80	115	—	—	—
Molybdenum.........	120	39.9	35,000	—	—	10	25	60	100
Brass (70% Cu and 30% Zn).........	123	39.2	9,100	1	85	128	—	—	—
Stainless steel (18% Cr and 8% Ni)............	163	71.4	20,300	—	15	28	—	—	—
Titanium alloy 75-A............	203	56.0	11,200	—	—	—	30	66	—
Steel 4130........	258	91.0	21,000	—	—	—	32	55	—
Tungsten..........	350	418.0	35,700	—	—	0	0	3	12
Titanium alloy 130A 92% Ti and 7.9% Mn).............	351	91.0	11,200	—	—	0	3	16	—
Titanium alloy 150A (96% Ti; 2.7% Cr and 1.3% Fe).....	437	105.0	11,200	—	—	0	0	3	26
Stellite (55% Co; 33% Cr and 6% W..	495	70.0	25,200	—	—	0	3	14	29

Puncture time of a plate by a stream flowing at a rate of 540 m/s was fixed. The results are given in Table 6.

Table 6

Material of plate	Puncture time, s
Aluminum..........	5
Duralumin.........	12
Brass.............	26
Bronze............	43
Steel Zh4.........	135
Steel 40Kh........	180

Results of an investigation of a wide class of metallic materials on erosion wear under slot flow of water conducted in the [VTI] (ВТИ) are presented in the article of V. G. Zelenskiy [60].

Comparing results of tests of erosion resistance of different metals, conducted by various methods, it is possible to ascertain that the greatest erosion resistance is possessed by hard alloys of the stellite and sormite type. Then follow tungsten, hard titanium alloys and chrome-nickel steel. Austenitic chrome-nickel steels have considerably higher erosion resistance than perlitic. Low erosion resistance is peculiar to case iron, carbon steel nickel and pure titanium. The lowest erosion resistance is fixed for aluminum. Within limits of defined groups of materials (carbon steel, chrome-nickel austenitic steel, and others) erosion resistance is greater the greater the hardness of the metal.

CHAPTER THREE

MECHANISM OF EROSION DAMAGE

8. Preliminary Remarks

The form of liquid motion under whose influence erosion damage of parts appears can be completely varied. Impacts of drops of condensate on blades of steam turbines, formation of cavitational zones for high speed ship propellers and blades of hydroturbines, flow of liquid near sealing surfaces of high-pressure fittings, rapid oscillation of parts immersed in liquid (for example, components of ultrasonic equipment), drops of rain on surface of aircraft flying at supersonic speeds, flow of grease in bearings and gear transmissions, etc. As numerous investigations of this question showed [49, 64, 56, 76, and others], in spite of the external variety of forms of interaction of liquid with a hard surface in the given examples, character and cause of damage in many respects are analogous. Causes of damage are either direct impact of drops or stream of liquid on surface of component, or phenomena appearing during deformation of cavitational bubbles on surface of or near eroding component. It has turned out that during erosion damage of blades of steam turbines under the influence of drops of condensate striking their surface or near the eroding component both these causes are closely connected. Therefore for deeper understanding of phenomena occurring under the impact of drops on a solid, it is necessary to examine also peculiarities and mechanism of cavitation erosion, when damage of a part is caused only by influence of cavitation bubbles in direct proximity with its surface.

Even in 1937 [61] Vater ascertained an analogy of the character of erosion damage from impacts of drops of condensate on blades of steam turbines and

cavitational damage of parts flowed over by a high-speed flow of water. However direct proofs of the fact that mechanism and original cause of these destructions are identical were not published until recently. In recent years in various countries several experimental works appeared whose analysis makes it possible to sufficiently specifically outline these connections and compose a defined concept about the mechanism of erosion damage under repeated impacts of drops.

9. Phenomena Occurring Under the Impact of a Drop of Liquid on the Surface of a Solid Body

In recent years several experimental investigations appeared about the impact of a single drop of liquid on the surface of a solid with the help of high-speed filming and other contemporary methods [9, 48, 77, 79, and others]. The character of deformation of a drop and the flow appearing after contact of a drop with the surface of a solid were investigated in a wide speed range of collision - from several meters per second [9] to hundreds [77] and even up to 1,000 m/s [79].

Investigations were also conducted on the destructive ability of individual drops at high-speed collisions of drops with samples from various materials [48, 79]. These investigations give a key to understanding the mechanism of erosion damage of blades of steam turbines.

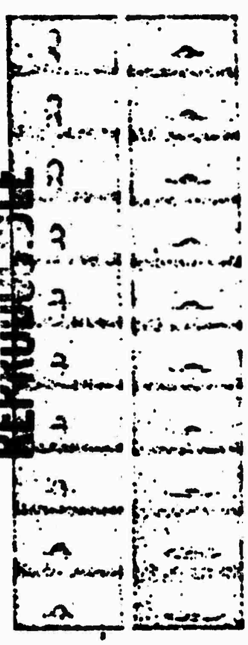


Fig. 31. Deformation of a drop falling on a solid surface from a height of 0.5 m.

Engel [9] studied the behavior drops of water falling on a glass plate from heights up to 6 m using high-speed photography (up to 15,000 frames per second) and a special optical system which allowed filming from different points. He applied also chemical methods of visualization of the spreading of a drop along a surface.

Consecutive stages of the spreading of a drop are presented in Fig. 31. As can be seen from the figure, upon impact at first there is a local flattening of the drop at the place of contact with the plate. Then spreading begins with the formation of a liquid disk against which rests the mound-shaped part of the drop, raised above the disk, until it is able to spread. Height of the mound gradually decreases until it completely disappears, whereas diameter of liquid disk with edging grows, i.e., radial spreading of drop occurs. The radial

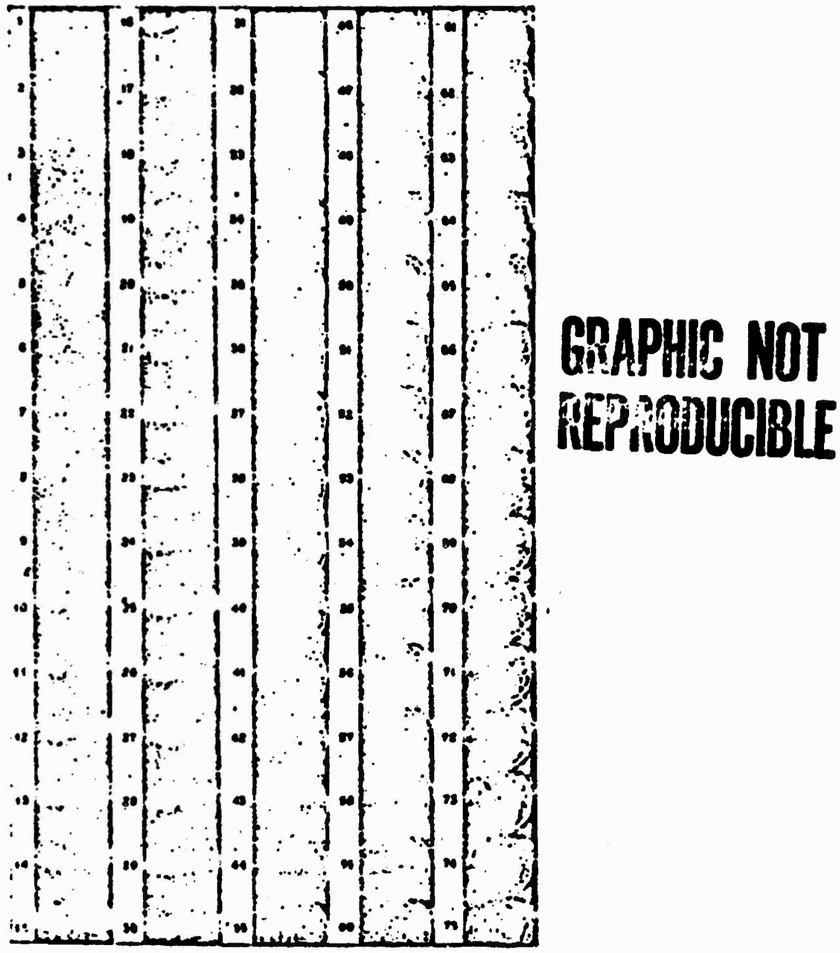


Fig. 32. Spreading of a drop along the surface of a glass plate.

velocity at which a drop spreads along the surface of a plate was determined by Engel both theoretically and with the help of photography, shown in Fig. 32 and taken with a time interval between frames of 0.000095 s through glass against which the drops fall. The experimentally found change of radius of spreading drop and speed of radial flow in time is represented in Fig. 33. It was established that maximum velocity of radial flow is several times higher than collision velocity (in Fig. 33, 8.6 times). An analogous result was obtained by other authors at collision velocities of a drop with hard surface of several hundred meters per second [77 and 78]. As can be seen from Fig. 33, reduction of speed of radial flow occurs very rapidly. It decreases up to a collision velocity by less than 1/1000 s, i.e., before the mound remaining from the drop disappears when the drop spreads along the surface.

One of the most important results of Engel [9] is the experimentally established

fact of appearance and development of cavitation bubbles in a drop spreading along a hard surface after impact. It was found that cavitation bubbles appear in a spreading drop even at low collision velocities of drop with plate, for example, 8.2 m/s. In Fig. 32 bubbles are seen especially distinctly in the central part of frames 40-44. Upon increased velocity the probability of appearance of cavitation bubbles in a drop considerably increases. It was established that time of existence of a cavitation bubble in a spreading drop is near 0.0014 s. For explanation of mechanism of appearance of cavitation bubbles in a drop striking the surface of a solid, in [9] two hypotheses are given:

1. A cavitation bubble appears at high velocities in radial flow, when pressure descends to value of pressure of saturated vapor.

2. Upon impact of drop at point of contact of drop with surface of solid a compression wave appears, which, spreading along the drop, is reflected from the drop-air interface and returns to point of impact in the form of a rarefaction wave. In the zone of rarefaction cavitation bubbles appear.

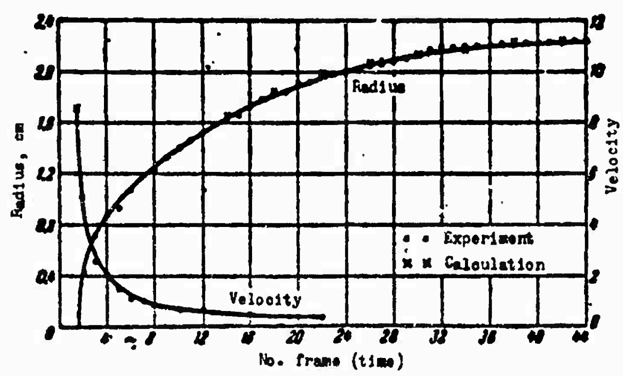


Fig. 33. Dependence of radius and velocity of radial spreading of drop on time; velocity of radial spreading of drop is collision velocity equal to 8.2 m/s.

It is generally known that cavitation bubbles promote cavitation erosion. Inasmuch as they are revealed in drops spreading after an impact against a hard surface, to understand the mechanism of erosion damage under the impact of drops it is necessary to understand mechanism of damage during cavitation erosion. This question will be examined in §§ 10 and 11.

Experimental data about the destructive ability of individual impacts of drops

are given in a number of works (see, for example, [48 and 77-79]). Authors of [48] investigated damage of different metallic and nonmetallic materials of drops of water of cylindrical form (diameter 1 mm, length 20 mm, mass approximately equal to mass of a large rain drop) at collision velocities up to 1050 m/s. It was established that under single impacts of drop at a velocity of 900 m/s even as hard a material as uranium carbide is deformed. A typical example of deformation of high-strength stainless steel under a single blow of a cylindrical drop is shown in Fig. 34. In the same place is shown profile of deformed surface – curve b.

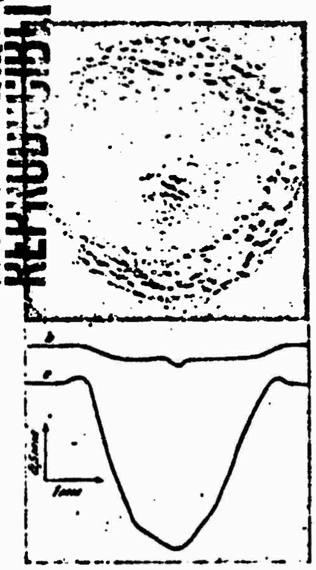


Fig. 34. Surface deformation of stainless steel (photographs and curve b) and aluminum (curve c) from the impact of a drop at a velocity of 760 m/s.

Upon impact a shallow saucer-like depression will be formed with deeper central depression and annular edging whose form resembles the surface of a blade of a steam turbine. For comparison Fig. 34 shows a depression made in aluminum under the same conditions (curve c). Diameters of damage of aluminum and stainless steels are identical, but depth of damage of aluminum is 8-9 times more than depth of damage of steel. With increased viscosity of liquid (replacement of water by a water-glycerine mixture) characteristic deformations for rim are increased. Consideration of pictures of metal damage (Fig. 34) clearly shows that the central depression appears directly from impact of drop on surface of metal. Analogous picture is obtained in [79].

Inasmuch as single impacts of a drop of liquid promate rather considerable damage of such hard materials as stainless steel, upon the impact of a drop against a hard surface high local pulse pressures must appear. Direct measurement of these pressures is sufficiently difficult since the zone of their action is small. Theoretical research of pulse pressures appearing upon impact of liquid against solid presents interest. On this subject several works have been published, however till now it was impossible to consider the question solved finally. In one of the recent works [80] M. I. Khmel'nik, determining pulse pressure under impact of liquid, proposes a method allowing calculation for an arbitrarily assigned form of drop after impact. Practical applicability of this method for concrete calculation still awaits

verification considering that the author examines a strongly schematized picture of the phenomenon. Appraisal of pulse pressure p, appearing under impact of a drop of liquid on a solid can be performed by the formula obtained by Engel [9]:

$$p=\frac{\alpha}{2}a_{ж}\rho_{ж}v, \tag{12}$$

where v – collision velocity;

$a_{ж}$ – rate of propagation of compression wave in liquid;

$\rho_{ж}$ – density of liquid.

In structure formula (12) is analogous to the well-known formula determining increase of pressure under a water hammer. Coefficient α considers specific character of the examined case of impact of a drop. Engel [9] affirms that at high collision velocities coefficient α probably will be close to unity.

10. Peculiarities of Erosion Damage During Cavitation and the Views of Various Researchers on the Mechanism of Cavitational Erosion

Cavitation is the formation in liquid of breaks (cavitation recesses, cavities, cavitational bubbles) under the action of great tensile stresses appearing either during flow-around bodies placed in liquid or during propagation of ultrasonic oscillations in it. During pressure fluctuations in volume of liquid cavitational bubbles alternately appear and vanish, remaining approximately in the same section of liquid. In a flowing liquid cavitational bubbles appear where with increase of velocity pressure in the flow, in accordance with Bernoulli equation, descends to the value of pressure of saturated vapor. Then cavitational bubbles are removed by the flow, enter the zone of raised pressure and are destroyed (collapse). Volume of a cavitational bubble can be from fractions of a cubic millimeter to several liters and even several cubic meters [81].

A collapse of liquid occurs in a "weak place." These weak places (centers of cavitation) in contemporary opinions [82] can be bubbles of vapor appearing in the liquid as a result of thermal fluctuations, and the smallest bubbles of air or other gas dissolved in liquid. A collapse can occur also on the boundary of liquid with a solid surface of a suspended particle or during passage through liquid of elementary particles possessing high energy.

Development and collapse of a cavitation bubble is accompanied by a complex of mechanical, electrical, chemical, thermal, acoustic and light phenomena. Study

of cavitation is hampered by the fact that in various conditions different sides of the phenomenon appear unequally. Cavitation has been studied no longer than one hundred years, and, in spite of hundreds of investigations conducted in various countries, thus for much in this phenomenon is still not clear. In particular, there are no firm, well approbated methods of calculation of temperatures and pressures appearing during shrinkage of a cavitation bubble; nature of the glow of cavitation bubbles is rot clarified, and, finally, there is no single opinion with respect to the mechanism of cavitational erosion.

Upon the collapse of a cavitation bubble there appear intense impulses of pressures (shock waves). According to certain evaluations made under a number of simplifying assumptions, pressure peaks can attain very large values (up to $\sim 10^3$ kgf/cm^2) [82]. Compression of a cavitation bubble is accompanied by increase of temperature and pressure of the substance in it. Theoretical calculations of these values give many different values up to 10,000 kgf/cm^2 and 10,000°K [82 and 83]. Measurements of the temperature inside cavitation bubbles during their compression, carried out by the method self-ignition of the substance in them, give more moderate values from $\sim$500 to $\sim$900°K [81 and 82].

During cavitation in certain substances (for example, in glycerine, ethylenegly ethyleneglycol, transformer oil) a glow of the bubbles is observed, called sonoluminescense. The cause of this phenomenon so far is not clear [82]; however, it has been established that the glow appears on the last stage of compression of a cavitational bubble. Therefore certain researchers connect sonoluminescense with heating during compression of gas in cavitational bubble (see, for example [83]). Others are inclined to attribute the cause of the glow to microscopic electric discharges in cavitational bubbles [84].

Finally, cavitation is accompanied by characteristic noise and damage (erosion) of parts which are in the cavitation zone. It was determined that during cavitation in water upon an increase of water temperature from zero to 50-60°C erosion damage increases a few times, and upon further increase of temperature weaken and then absolutely vanish at 100°C. During cavitation of other liquids the cavitation influence upon nearing boiling point also weakens. Experiments showed [85] that intensity of erosion essentially depends on difference of external pressure and vapor pressure. If this difference is equal to zero, erosion is not observed. With increase of surface tension of liquid erosion wear considerably increases [49].

The first attempt to explain the mechanism of erosion damage during cavitation was made by Cook and Parsons [86]. They considered the cause of erosion damage to be direct impacts of liquid during rapid collapse of cavitation bubbles. It was assumed that the impact occurs on a solid placed inside the cavitational bubble. However such a model does not have real meaning, since actually the bubble is on the damaged surface or near it, i.e., a water hammer should occur at full closing of bubble. But the formula of Cook is inapplicable for this case, since when $R \to 0$ it gives an infinite pressure value.

Rayleigh [87], removing these difficulties of the theory of Cook, developed a theory of the destructive action of cavitation, according to which damage occurs not from direct impacts of liquid on the metal surface, but because of the influence of high pressures appearing in the vicinity of the cavitational bubble during its shrinkage. Rayleigh examined the following problem. In an infinitely extended mass of liquid on which pressure acts overall, suddenly a spherical cavity is created. It is required to calculate speed of shrinkage of cavity and pressure in the spherical shock wave appearing upon shrinkage of cavity. Considering the liquid to be incompressible, disregarding viscosity and assuming that inside the cavity (bubble) is a vacuum, Rayleigh found that maximum pressure appears at 1.57 R_0 from the center of collapse and is equal to:

$$p_{\text{макс}} \approx 0{,}163\left(\frac{R_0}{R}\right)^3 p,$$

where R_0 – initial radius of bubble;

R – radius of bubble at the examined moment of time;

p – hydrostatic pressure in liquid.

The theory of Rayleigh has been widely used for a long time in explaining the nature of cavitation erosion. Recently works have been published in which the authors try to definitize separate positions or to solve the problem rejecting certain assumptions of Rayleigh. For example, in [88] the problem of collapse of a spherical empty cavity is examined taking into account compressibility of water, but neglecting forces of viscosity and surface tension. In article [89] the problem of collapse of a spherical bubble filled with vapor is solved taking into account thermal conduction and condensation of vapor on boundary of bubble with liquid. The obtained solution in limit (when pressure of vapor in bubble is assumed equal to

zero) leads to the solution of Rayleigh.

Calculation by the formula of Rayleigh or by definitized formulas can be obtained values of maximum pressures equal to many thousands of atmospheres, i.e., at first glance one would think it is possible to explain erosion damage of metals. However, as experimental investigations of the character of damage of cavitation bubbles have shown,[1] during deformation they do not simply change diameter, but also lose the form of a sphere and even break up into separate parts. Therefore the scheme examined by Rayleigh does not correspond to the real picture of the phenomenon and cannot serve as an explanation of the nature of erosion damage.

Much attention was given to investigation of the nature of erosion damage during cavitation at the international symposium on "Cavitation in Hydrodynamics" [90], which took place in 1955 in England. Discussion of this question at the symposium reflects the struggle of ideas and opinions of supporters of mechanical, chemical-mechanical, electromechanical, thermochemical, and other theories of erosion.

Author of a survey report Eisenberg [91], noting that it is impossible to examine all accumulated extensive and contradictory material about the mechanism of cavitation erosion, and examining several works of a number of authors, arrives at a conclusion about the mechanical nature of destructive forces and about the fact that further success of investigations in this region is connected with successes of investigations of fatigue strength of materials. He considers that it is important to establish a connection between electrical phenomena and mechanical damage appearing during erosion.

In this connection it is necessary to note the report of Wheller [92] about his experiments on a magnetostrictive instrument, conducted in order to clarify the extent of participation of mechanical and chemical factors in erosion damage. Experiments were conducted in water, in a KCl solution, and in toluene in which ordinary corrosion of metals is not observed. In examining the mechanism of cavitation erosion Wheller proposes to distinguish two cases: 1) in a noncorrosive liquid shock pressures during destruction of cavitation bubbles (if force of impact is higher than yield stress) induces a shearing strain on microsections, especially near boundaries of grains, which in the end will lead to a chipping of grains. It allows possibility of local increase of temperature under the action of cavitational

[1]More detail about this will be presented in the following section.

impacts; 2) in chemically active corrosive liquids under certain conditions part of the weight losses from corrosion supposedly can attain 50% of full loss of weight of sample during erosion. However Wheller recognizes that during intense cavitation the portion of losses from mechanical influence undoubtedly predominates.

Rasmussen [93], as the authors of many works, is a supporter of the mechanical theory.

Knapp in his report at the symposium [94] and in [95], remaining within the bounds of the mechanical theory of erosion damage, arrives at the conclusion that damage is not connected with fatigue of material, but is caused by a small number of very intense impacts on a given element of the surface.

Callis [96], in a report on the mechanism of cavitation damage affirms the predominant role of corrosion in damage, i.e., supports the electrochemical theory of erosion.

The electrochemical theory of erosion damage in its purest form explains erosion wear by continuously occurring chemical and electrochemical processes, which promote corrosion. Destruction of cavitation bubbles supposedly only accelerates these processes, causing an increase of temperature and pressure. The role of the flow from this point of view leads only to removal of products of corrosion. Protectors of such a point of view are few [96 and 97], inasmuch as the opinion of chemical processes as a basic cause of erosion damage is not confirmed. In this connection it should be noted that such chemically passive materials as agate, concrete, gold, and others are subject to erosion [85]. There are well-known examples of very intense erosion, when straight-through erosion damage of a metallic plate by a high-speed stream of water occurs in several seconds [47] or strong erosion appears from several impacts of large drops [48, 79, and others]. In such a brief time of erosion damage it is senseless to speak of a predominant role of corrosion. Investigating more than thirty different materials in sea water, authors [43 and 98] came to the conclusion that speed of erosion damage upon cavitation exceeds speed of corrosion damage on the average by more than four orders. During cavitation in nonaggressive liquids chemical processes only accompany the basic mechanism of erosion action, preparing the component for subsequent easier damage, and thereby accelerate the damage process. Confirmation of this point of view can be found in many publications (see, for example, [60, 92, 99, 101, and others]). It

is possible to assume that cavitation erosion in aggressive media will occur more intensely than in nonaggressive, since the share of participation of the chemical factor in erosion damage will increase with increase of aggressiveness of medium [61 and 92].

Zelenskiy [60] considers that electrical currents appearing between surfaces of metal flowed around with different speeds, strengthen effect of corrosion damage during cavitation.

Character of change of electrical potential at impact of a stream of water against a metallic surface was investigated by Noskievis [102] on an erosion installation of the type shown in Fig. 18. In a nest made of insulating material is fastened a sample which by an electric lead is connected with an insulated slip ring to a shaft and further through carbon brushes — with an oscillograph. To measure the potential induced by the impact on the sample of a water stream, emanating from a nozzle, in the nozzle was placed a ring insulated from the housing and made of a material identical to the sample. With the help of an oscillograph electrical potentials upon blow of water against carbon steel, stainless steel and brass were investigated. It was shown that as a result of the impact of liquid against the metallic surface along with mechanical action electrical currents appear which render an electrochemical influence on the metal. Change of potential depending upon number of turns of shaft is shown in Fig. 35, from which it is clear that potential almost linearly depends on number of turns.

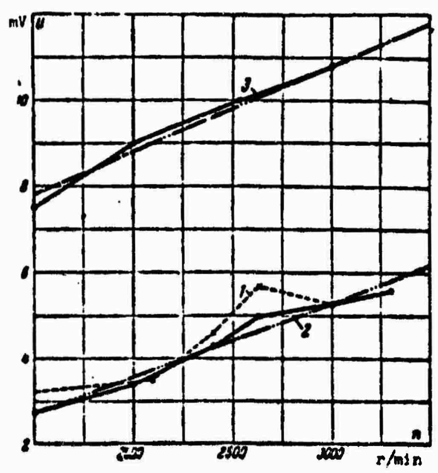


Fig. 35. Change of electrical potential U between ring and sample depending upon number of turns n. 1 and 2 – ring is made of gray cast iron; 3 – ring is made of brass.

Noskiyevich [99] indicates that electrical currents appearing during cavitation can be explained by the heating of metal. The closing cavitation bubbles promote local heating of surface of metal, leading to thermoeffect. Increase of temperature is estimated within limits from several degrees to 250°C. Heated and unheated parts of the metal surface will form a thermocouple whose electrical current promotes electrochemical processes during cavitation. Thus, along with mechanical damage of metal (primary effect) electrochemical corrosion (secondary effect) occurs.

Nechleba [100] affirms that the greatest value of thermoelectric is in the initial period of damage. Then, when cracks and pores have already been formed on the metal surface, the predominant action of mechanical causes begins. These results will fully agree with data obtained by Noskiyevich in his experiments with cathode protection from erosion (see below § 17).

A number of works, directed towards clarification of character and nature of erosion during cavitation induced by stalled flow-around bodies, was published by K. K. Shal'nev. He proposed to introduce a power parameter characterizing cavitation erosion, and studied the scaling effect of cavitation erosion [103, 104].

Finishing the survey of different views on the mechanism of cavitation erosion, we stress that the majority of researchers is inclined toward mechanical theories. The most orderly and experimentally corroborated explanation of the mechanism of erosion damage during cavitation is given by M. Kornefeld and L. Ya. Suvorow [8]. A description of their opinions is given below.

11. Mechanism of Erosion Damage During Cavitation According to M. Kornefeld and L. Ya. Suvorow, and Development of Their Ideas in the Works of Other Researchers

Theoretical calculations of Cook and Rayleigh, mentioned in the preceding section, are based on the concept of a cavitation bubble preserving spherical or hemispherical form during its entire existence. However, in reality the situation is otherwise. This was first clearly shown[1] by M. Kornefeld and L. Ya. Suvorow in [8], written on the basis of an investigation conducted in 1939-1940 at the Academy of Sciences, USSR. Conducting optical investigations and photographing cavitation on a magnetostrictive vibrator, they established that cavitation bubbles very easily lose stability of form. A bubble preserves spherical form only on the first stage of shrinkage, then it is sharply deformed and even divided into parts (see Fig. 36, taken from [8]). Causes of instability of bubble are the fact that, besides forces of surface tension, which condition the spherical form, on the surface of the bubble act hydrodynamic forces, connected with motion of the bubble (forward, oscillations, pulsations, etc.). As soon as hydrodynamic forces exceed the force of surface tension, the bubble is deformed.

Later an analogous picture of the behavior of bubbles was observed by other

[1]Method and results of these experiments are described in Russian in the book of M. Kornefeld [50].

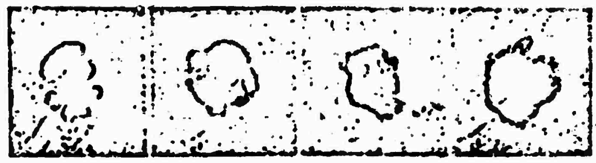


Fig. 36. Different phases of deformation of a bubble.

researchers (see, for example [76 and 105]). S. P. Kozyrev [76] investigated separation cavitation after a round profile in a hydrodynamic pipe and established that change of form of cavities in separation cavitation are analogous to changes which both Kornefeld and Suvorow observed during ultrasonic cavitation. He showed that pressures appearing during shrinkage of a bubble and time of existence of bubble, calculated by the formula of Rayleigh, will not agree with experimental data, and the theory of the destructive action of cavitation proposed by Rayleigh is inapplicable to cavities of separation cavitation.

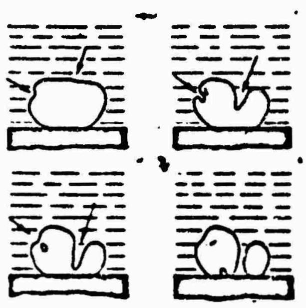


Fig. 37. Impact of stream of liquid on surface of solid body during deformation of cavitation bubble.

M. Kornefeld and L. Ya. Suvorow explained erosion damage during cavitation by direct and repeated water hammers of streams (tongue) of liquid, appearing during deformation of a bubble. Formation of such a stream of liquid, initially entering the bubble and then striking the surface of the solid near which is the bubble, is visually demonstrated in Fig. 37. Direction of travel of stream is shown by arrows.

The explanation M. Kornefeld and L. Ya. Suvorow gave about the mechanism of erosion damage during cavitation has received ever increasing fame, acknowledgement and additional confirmations in the works of both Soviet and foreign scientists (see [4, 47, 49, 76, 81, 98, 105, 106, and others]). In article [105], for example, it is shown that a stream entering a bubble and damaging the surface of the sample by direct contact could be detected and observed experimentally, and that the action of this stream will agree with theoretical calculations. According to theoretical data [105] velocity of the stream striking the surface a body can attain 1,000 m/s. Direct measurements of deformation of bubbles of separation cavitation after a round profile flowed around at 17 m/s showed [76] that speeds of shift of surface of bubbles during their

compression (i.e., velocity of streams of water entering bubble), attain 90 m/s.[1]

In works of Glikman and others [43 and 98] theory of the destructive action of cavitation was further developed. They give experimental data obtained during investigation of surface layer of samples subjected to cavitational action on a magnetostrictive vibrator. Analysis of the microstructure of samples subjected to cavitation established that on the first stage of damage in the surface layer of the sample there is plastic deformation and cold hardening occurs at a depth of several tens of microns.[2] This occurs under the action of repeated water hammers. With increased duration of cavitational influence the microdeformation picture is intensified and, starting from a certain moment, the appearance of microscopic cracks and chippings is observed.

Each bubble locked to the surface of a part embraces a very small region (according to experiments of M. Kornefeld and L. Ya. Surovow diameter of bubbles is several tenths of a millimeter, and the stream of water entering the bubble has considerably smaller dimensions). Zone of maximum stress under a water hammer is commensurable, obviously, with dimensions of separate structural components — an order of one or several tens of microns. The magnitude of these stresses is very considerable and for the majority of technical materials exceeds the level of yield stress. Therefore for materials nonuniform in structure damage occurs first in a less strong structural component.

From what has been said it follows that cavitation resistance is determined not so much by the average properties of macroscopic volumes, as much as by properties of microscopic volumes, i.e., strength of separate structural components and their groups. When there is unfavorable distribution of a low-strength structural component, its damage leads to the chipping of a comparatively larger particle of stronger structural components. The onset of cracks and chipping occurs on grain boundaries.

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[1]These data have been obtained on the basis of treatment of high-speed filming of the deformation of cavitation bubbles.

[2]According to other data [71] depth of the cold hardened layer can reach almost 0.3 mm.

12. Mechanism of Erosion Damage from Impacts of Drops on the Surface of a Hard Body

The analysis of investigations of cavitation erosion and collision of drops of water with solids given in preceding sections of this chapter permits conceptualizing the mechanism of erosion damage under water-drop impact.

At low collision velocities, when pressures appearing upon water-drop impact against a surface is less than elastic limit of material, erosion damage at first glance need not appear. However, in reality, under multiple impacts of drops they occur visibly due to mechanical action of water upon loss of stability of form and asymmetrical closing of cavitation bubbles appearing as the drop spreads along the surface of the part. It has been established [9, 77, and 78] that speed of radial flow as drops spread along the surface is a few times higher than collision velocity, and cavitation bubbles appear in drops even at a collision velocity of 8.2 m/s [9]. With increase of collision velocities the spreading rate of a drop along the surface increases, i.e., more favorable conditions are created for formation of cavitation bubbles in a drop and erosion damage is intensified.

At high collision velocities erosion damage appears not so much at loss of stability of form and disintegration of cavitation bubbles in a drop as much as from direct water hammers of a drop on surface of part. Destructive ability of water-drop impacts at collision velocities of several hundreds of meters per second is so great that the impact of one drop can produce noticeable damage of even as hard a material as uranium carbide [48].

Thus, there is not fundamental difference between the mechanism of erosion damage at high and low or moderate collision velocities of drops with hard surface. In each case damage occurs from water hammers against surface of component. Only at high collision velocities is the force of a water drop impact so great that damage occurs from one impact and dimension of damage is commensurate with diameter of striking drop. At low or moderate collision velocities every water hammer appearing upon asymmetrical closing of a cavitation bubble at the surface of a component acts on a microscopically small section of surface, therefore noticeable erosion damage does not appear at once, but only after numerous impacts.

In turbines working on steam, relative velocities of drops of condensate at impact on the leading edge of a rotor are not so great that they directly promote damage of material, inasmuch as it is well-known that erosion wear of blades does

not appear at once. Here a basic role in erosion damage (in any case on its first stage, when deep pits still have not formed and there is no chipping of grains of material under the action of impacts of individual drops) belongs obviously to water hammers appearing when there is asymmetrical closing of cavitation bubbles which appear as the drop spreads along the blade surface. Such an explanation makes evident the long established fact [61] that the character of erosion damage from the impact of drops of condensate on blades of steam turbines and cavitation damage of parts washed by a high-speed flow of water is identical.

The role of the chemical factor in erosion damage during operation on water or on moist steam is insignificant. However it can increase in the case of application of aggressive liquids (for example, when a turbine works on vapors of alkali metals at high temperatures [12]).

CHAPTER FOUR

PREVENTING OF EROSION OF STEAM TURBINE BLADES

It is well known that even in the case of a reheat vapor moisture in the last stages can reach 5-8%. In combination with high peripheral velocities of blades of last stages, which for contemporary turbines reach $u_{\text{пер}} = 565$ m/s, this is fully sufficient to cause erosion damage of the best materials used in the manufacture of blades if no special measures were taken to shield blades from erosion [20, 107, and 108]. Protective measures can have an especially important value for turbines of atomic and geothermic electric power stations. In these turbines sometimes not only the last stages but also high pressure stages work on moist vapor.

There exist various methods of preventing erosion of turbine blades. Inasmuch as the cause of erosion is the impacts of drops against blade surfaces, one of the most effective methods of its prevention is dissipation of condensate from flow-through part of turbine with the help of separational devices. Considerable reduction of erosion can be obtained by surface and local strengthening of the blade sections most subject to erosion. Rational selection of structural and gas-dynamic parameters in the protection of turbines has an essential value in decreasing erosion. Finally, there is some information about electrical shielding from erosion. We will examine all these methods in detail.

13. General Information on Moisture-Catching Devices in Turbines

The following phenomena are mainly used for separation of moisture in condensation turbines:

1) repulsion of film of condensate along surface of blades of rotor to periphery due to centrifugal forces appearing during rotation of rotor;

2) repulsion to periphery of drops of condensate in axial clearance between nozzle box and rotor (see above § 3);

3) dispersion of moisture together with vapor sucked into the separational device;

4) immediate dispersion into separational device of film of condensate moving along parts, forming contour of flow-through part of turbine;

5) inertial forces acting upon drops of condensate as flow turns in curvilinear channels.

Inasmuch as a considerable part of moisture is flung to the housing along the blade surface of rotors, the separation device is conveniently placed directly after the rotor. Then the removed condensate no longer will render a harmful influence on work of subsequent turbine stages.

If in the vapor flow proceeding from the preceding stage a considerable quantity of condensate already is contained, it is advisable to remove moisture with the help of a moisture-catching device located after the nozzle box. Such a device is successfully used before the rotor of the last stage by one of the most powerful contemporary domestic steam turbines K-300-240 at the Kharkov turbine plant [107].

Different plants and firms use moisture-catching devices which vary extensively in structural design (see, for example, [3, 4, 21, 22, 38, 107-111]). However, until recently there were published extremely few systematic investigations which would permit a designer to select confidently the most rational parameters of a moisture-catching device for any specific conditions.

Usually it was considered that good designs of moisture-catching devices permit removing from the flow of moist vapor in the flow-through part of a turbine up to 40% of the condensate contained in it [112] or up to 50% moisture[1] exceeding 5% [6]. In a bad device this figure is a few times lower.

[1]Systematic investigations of models of moisture-catching devices conducted at the BITM by I. I. Kirillov and R. M. Yablonik on humid air at small peripheral velocities of rotation of rotor ($u < 100$ m/s) give higher values (see the following section). However subsequent experiments conducted at the LPI on an experimental steam turbine in a wide range of peripheral velocities showed that at $u > 100$ m/s separation undergoes essential changes, and sharply worsens (see pp. 495-496 of the recently published book of I. I. Kirillov [126]).

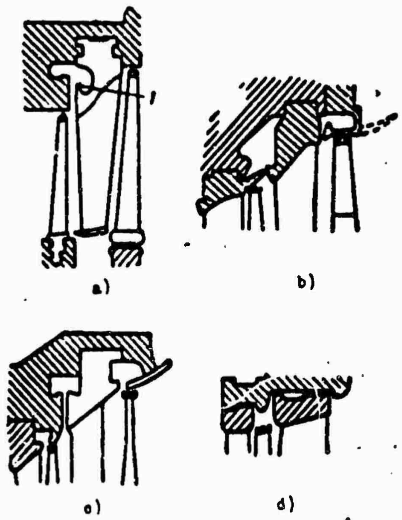

Fig. 38. Moisture-catching arrangements without vapor suction. a) Westinghouse turbine, 150 MW; b) General Electric turbine, 160 MW; c) Allis-Chalmers turbine, 100 MW; d) Metropolitan-Vickers turbine, 50 MW.

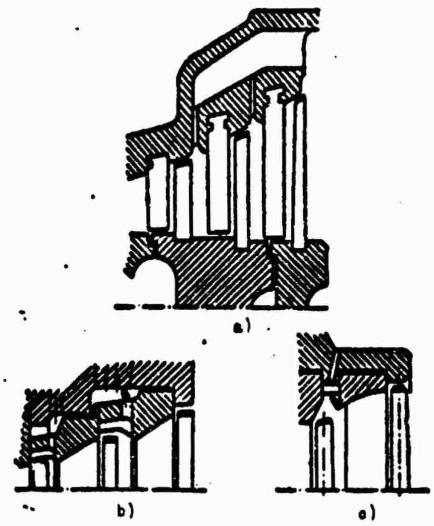

Fig. 39. Moisture-catching arrangements with vapor suction. a) Brown-Boveri turbine, 20 MW; b) Escher-Wyss turbine, 60 MW; c) Alstom turbine, 100 MW.

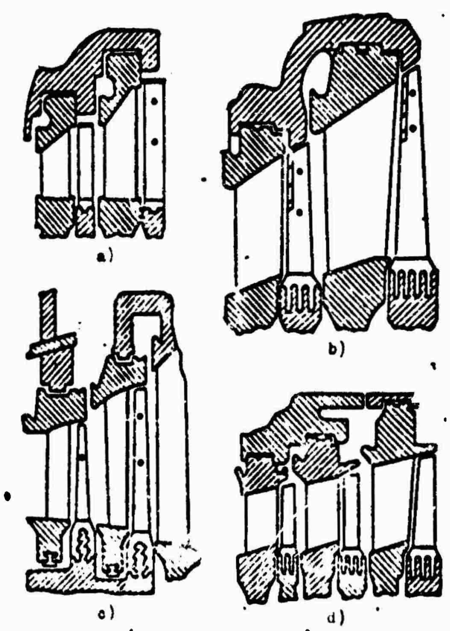

Fig. 40. Moisture-catching devices. a) [KTZ] (КТЗ) design (turbine [AP-6] (АП-6)); b) [LMZ] (ЛМЗ) design, c) [KhTGZ] (ХТГЗ) design; d) [NZL] (НЗЛ) design.

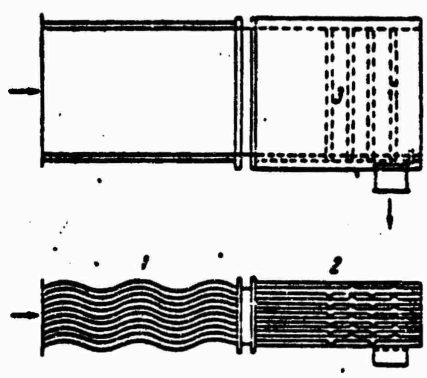

Fig. 41. Diagram of Brown-Boveri separator.

Figures 38-40 represent several examples of moisture-catching devices applied in domestic and foreign turbine constructions. A Westinghouse device (Fig. 38a) is characterized by moisture-delaying projections 1, preventing return of separated moisture into the flow-through part of the turbine. In General Electric and Allis-Chalmers arrangements (Fig. 38b and 38c) separation of moisture is carried out after both

the rotor and stator blades. It is doubtful whether the feature in the Metropolitan-Vickers separation arrangement of a 90° turn of the moisture-leadoff (Fig. 38d) in front of the moisture-catching chamber is justified.

Figure 39 shows several separational arrangements in which for separation of moisture along with using the repulsion of drops along the surface of rotor blade there is a forced vapor suction from flow-through part of turbine into the separational device. The long and narrow moisture leadoff in the Brown-Boveri design (Fig. 39a) in contemporary opinions based on results of detailed parametric investigations (see the following section) cannot be recognized as a top quality separational arrangement. In the Escher-Wyss moisture-catching arrangement (Fig. 39b) the moisture leadoff is considerably broader. Moisture delaying projections and in open arranged inlet to the moisture-catching chamber is characteristic for the Alstom arrangement (Fig. 39c).

Features of moisture-catching devices of certain domestic steam turbines are seen from Fig. 40.

It is still necessary to mention several forms of moisture-discharge devices. As was mentioned above, in atomic power plants vapor is generated whose state as a rule is close to saturated. Installing the usual centrifugal moisture separators before the turbine leads to great losses of pressure and to reduction of efficiency. In order to eliminate this deficiency, the Brown-Boveri firm [113] designed a separator in which moist vapor touches large surfaces where water is precipitated in the form of a film (Fig. 41). The separator consists of two stacks of steel sheets: first stack 1 – wavy sheets, second stack 2 – smooth parallel sheets with grooves 3 for water drain. The separator was tested at one of the atomic electric power stations. It was established that losses in the separator are 2-3 times the dynamic pressure of flow on input.

In [3] a proposal to remove water through hollow blades of nozzle boxes is reported. Water should enter internal space of blade through holes in the wall forming the blade profile.

14. Results of Parametric Investigations of Moisture-Catching Arrangements

Recently at the Bryansk Institute of Transport Machine Building (BITM) and in certain other organizations of our country systematic parametric investigations

were conducted, directed towards a search for scientifically proved methods of creating effective moisture-catching devices, intended for separation of moisture from flow-through part of condensation turbines. A number of articles [13, 109, and 114-117] dedicated to this question have been published. Below is a brief account of basic results of these works. Experiments started in 1955 at the BITM were conducted on models of turbines with small peripheral velocities. The working substance was an air duct mixture, obtained by means of injection of water finely pulverized in injectors into the air flow in front of the turbine. Such method is attractive because of its simplicity, but does not permit modeling thermal processes occurring in a real two-phase flow of moist vapor. Results of these experiments permitted detailed investigation of the mechanical side of the phenomenon of separation and formulation of basic principles of the design effective moisture-catching devices. However, they should be examined only as initial material for subsequent definitizing experiments on stands and in natural conditions (see also [126]).

A basic characteristic of a moisture-catching device is the coefficient of moisture removal ψ, equal to the ratio of the flow of separated water to the total water flow on the stage inlet. Results of tests are given in the form of dependences of the coefficient of moisture removal on geometric parameters of the device and on degree of moisture of flow in the stage. Degree of moisture y implies ratio of mass flow rate of injected water to total mass flow rate of air duct mixture on given operating conditions of stage.

An investigation of the influence of geometric parameters of moisture-discharge devices located behind the rotor and nozzle box, degree of moisture of flow and suction of working substance on efficiency of moisture removal was conducted.

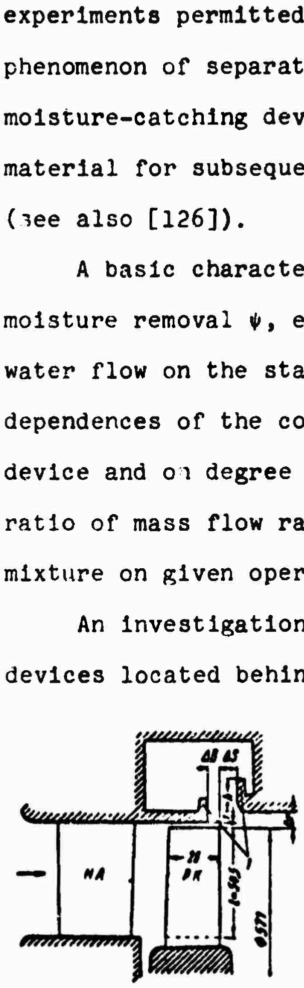

Fig. 42. Diagram of model of stage with moisture-catching device behind rotor. 1 – moisture-delaying projections.

A diagram of the investigated model of moisture-discharge device, placed after the rotor, is shown in Fig. 42, and results of testing a number of variants of such are shown in Fig. 43. The investigation showed that increased relative width of the moisture leadoff $\Delta\bar{S} = \Delta S/l$ (designations are in Fig. 42) from $\Delta\bar{S} = 0.032$ to 0.275 permitted an essential increase of effectiveness of moisture removal (Fig. 43a). At further increase of

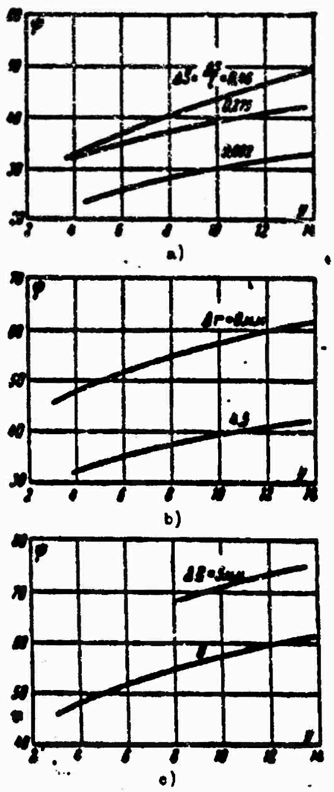

Fig. 43. Results of tests of moisture-catching devices behind the rotor: a) influence of width of slot ΔS (Δr = 4.5 mm; ΔB = = 0); b) influence of covering Δr (ΔS = 15 mm; ΔB = 0); c) influence of partial opening of face-surface of rotor blades ΔB (ΔS = 15 mm; Δr = 0).

$\Delta\bar{S}$ to 0.46 the increase of effectiveness of moisture removal is not as rapid.

Decrease of covering Δr from 4.5 mm to zero, other things being equal, lead to an almost one and a half times increase of effectiveness of moisture removal ψ (Fig. 43b). Consequently, in designing moisture-catching devices the covering must be decreased as much as possible.

The possibility of increasing effectiveness of moisture removal by partial transfer of the moisture-catching inlet to the zone above rotor blades was investigated also. i.e., partial opening of rotor blades ΔB (Fig. 42). Tests showed that opening the face-surface of rotor blades approximately to 20% of blade width hardly lowers efficiency of the stage, but permits an essential increase of effectiveness of moisture removal (Fig. 43c). Upon further increase of opening of face-surface of blades increased effectiveness of moisture removal is conjugate with lowering of efficiency of stage. Increased effectiveness of the moisture-discharge device with opening of face-surface of rotor blades is explained by the increased direct falling of drops of condensate from the surface of blades into the moisture-catching device.

The influence of moisture-delaying flanges 1 and height of rear wall of moisture leadoff h (Fig. 42) on effectiveness of moisture removal was experimentally checked. It was determined that every protrusion increases coefficient of moisture removal ψ approximately 3%. Decrease of height of rear wall of inlet section h (Fig. 42) leads to increased effectiveness of moisture-catching device. These experiments indicate possibility of improvement of the operation of moisture-catching devices due to a more open entrance into the moisture-catching chamber.

An analogous result was obtained in 1957-1958 at the [TsKTI] (ЦКТИ) during a test of four types of moisture-catching devices mounted behind the rotor of the last (sixth) stage of a 240 kW condensation turbine [109]. Diagrams and results of

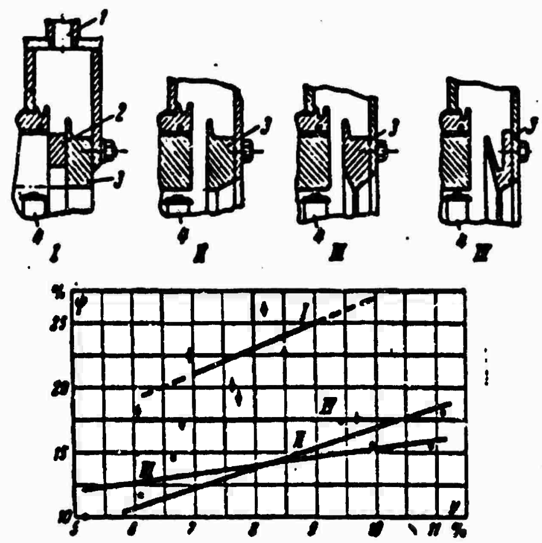

Fig. 44. Diagrams of moisture-catching devices and results of their tests (without vapor suction according to [109]. 1 – hole for vapor suction; 2 – guide inserts; 3 – moisture delaying ring; 4 – rotor blade.

tests of the investigated devices are represented in Fig. 44. The higher effectiveness of IV as compared to II and III is explained by the greater relative width of the inlet of the moisture leadoff with a constant width of 12 mm for the outlet from the channel and angle of slope of the rear wall forming the channel. The effectiveness of the moisture removing device with profiled guide inserts (variant I) is higher than effectiveness of devices without guide inserts (variants II, III, and IV).

An investigation of the influence of vapor suction to increase effectiveness of moisture-catching devices was made by I. I. Kirillov, Ya. M. Yablonik [13 and 115] and A. P. Astaf'yev [109]. On one hand suction promotes a decrease of erosion and losses connected with acceleration of condensate in the vapor flow, and also losses due to braking of the rotor upon impact of drops on the back of the blade; on the other hand, it promotes additional losses, since the vapor which has been sucked out no longer accomplishes effective work in subsequent stages. It was determined that to every percent of increase of the drawn-off vapor corresponds an increase of the outgoing moisture of not more than 0.25-0.3%. Based on these data and assuming that upon a 1% increase of humidity, the efficiency of a stage is decreased by 1.3%, R. M. Yablonik [115] concluded that the use of suction to

increase effectiveness of moisture-catching devices in the usual diagrams cannot be recommended, since it leads to a reduction of turbine efficiency. In [109] it is shown that application of suction favorably affects work of all four investigated moisture-catching devices. Obviously the question of rationality or irrationality of vapor suction in order to lower moisture content requires still further detailed and overall study taking into account that, for example, sometimes withdrawal of moisture is carried out together with steam extraction on preheating of water supply.

A parametric experimental investigation of the effectiveness of moisture-catching devices placed before the rotor is reported in [13 and 115]. Results of tests are represented in Fig. 45. From the graph it is clear that with increased axial clearance between blades of the guide vane apparatus and the rotor effectiveness of moisture removal increases. Such character of curves $\psi = f(z_1/\ell_1)$ is fully explained by the fact that with increased z_1 an even greater part of moisture from the twisted flow after the guide vane apparatus goes to the housing. On the housing will be formed a film of moisture having an axial component of velocity. If withdrawal of this moisture into the separational device is carried out along a profiled curvilinear surface (model II in Fig. 45), the effectiveness of the device is considerably higher than in model I, in which film breaks off from a sharp angle (cf. curves 1 and 2, Fig. 45). Tests [115] showed that in moisture-catching devices located before the rotor, just as in devices, placed after the rotor, a decrease of covering is favorably reflected on an increase of coefficient of moisture removal ψ.

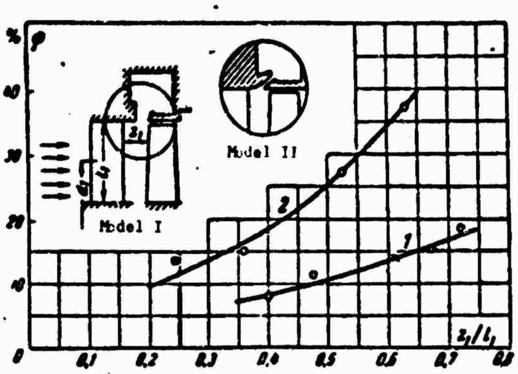

Fig. 45. Results of experiments of BITM with a moisture-catching device in front of rotor at ℓ_1 = 76 mm and

$$\frac{d_1}{\ell_1} = 7.3.$$

1 – for model I; 2 – for model II.

Summarizing the experiment of investigation of moisture-catching devices, I. I. Kirillov and R. M. Yablonik give general recommendations about optimum forms of these devices. Recommendations lead basically to the following. High effectiveness of moisture-removal after the rotor is attained due to a wide and short moisture

leadoff at minimum covering Δr and considerable (approximately up to 20% width of rotor) opening of vane channels of rotor on periphery. A considerable quantity of moisture in front of the rotor can be removed by a moisture-removal device with smooth entrance (Fig. 46).

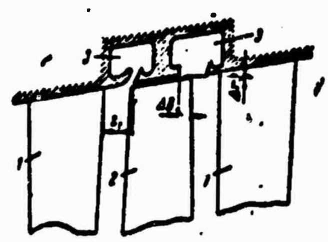

Fig. 46. Diagram of recommended BITM moisture-catching devices. 1 – stator blades; 2 – rotor blade; 3 – moisture-catching chamber.

15. Hardening of Surface of Blades

Inasmuch as erosion damage of blades of steam turbines starts from the surface of blades, different attempts were begun to combat erosion by way of hardening the surface of blades (chromium-plating, local hardening of edges of blades, cold hardening, nitration, putting cover plates of erosion-resistant materials onto the blades, hardening of surface layer by the electrospark method, etc.). It must be noted that different researchers have various opinions on the reason for the effectiveness of methods of hardening blade surfaces. This is apparently connected with distinctions in technology of putting on coverings and subsequent treatment of parts. Improvement of technology sometimes gives a decisive effect. It is necessary to stress that improvement of quality of external surface and adjacent layers of material gives a positive effect only when the surface layer is well joined with the basic material of the blade.

A number of researchers of the 1930's (see, for example, [2], where references are made to several more works) considered that a chrome-plated surface does not give the best anti-erosion qualities since the layer of chromium rapidly cracks and comes off. However, later it was reported that Czechoslovakian turbine builders successfully use electrolytic chrome-plating of the working surface of blades [37]. These results are fully understandable in the light of investigations conducted by

Glikman [43] (see section "b," § 7).

In [118] successful testing of blades with a cold hardened edge made of steel WF-100, and the positive effect of local hardening of edge of blades was reported.

As was already mentioned (section "b," § 7), there is no single opinion about whether it is possible with the help of nitration to increase erosion resistance of a part. Investigation of nitration for increasing erosion resistance of stainless steel [1Kh13] (1X13), intended for the manufacture of blades of steam turbines, was conducted at the LMZ. It was reported [119] that satisfactory results can be obtained if before nitration the passive film which constantly covers the surface of stainless steel and prevents penetration of nitrogen into the metal is destroyed by special treatment. A characteristic feature of a nitrated layer on steel 1Kh13 is a sharp drop of hardness upon transition from nitrated layer deep into the part. However, in spite of this deficiency, nitrated segments of high pressure turbine nozzles showed sufficiently satisfactory resistance under conditions of exploitation.

The Laval firm recommends diffusion nickel-plating of blades to prevent erosion [37].

In an article by Gardner [22] even in 1932 successful application of cover plates from hard materials (tungsten steel) soldered on leading edges of rotor blades from the back of the blade was reported. Cover plates are fastened only on the peripheral parts of blades most subjected to erosion (see, for example, Fig. 40b). Even at that time profiled cover plates with thickness variable with respect to height of blade were used. Gardner reports about experiments in which it was found that installation of such cover plates practically does not affect efficiency of turbine. He considered it advisable to apply protective cover plates on leading edges of blades simultaneously with devices for removal of condensate from flow-through part of turbine. This recommendation still holds true. In [5] it is indicated that practically the only effective method of combating erosion of blades of the last stages of steam turbines is the experimentally proved system of moisture removal in combination with cover plates from superhard alloys or with other methods of hardening leading edges of blades. The best material for hardening cover plates is considered at present to be stellite No. 1, containing 62% cobalt, 25% chromium, and 7% tungsten. This material yields to treatment and does not lose hardness when cover plate is soldered to blade. However such a method

of hardening blades can cause formation of cracks [5].

An advanced method of hardening the surface of blades of steam turbines at present is considered to be hardening by the electrospark method [5, 37, and 40]. The essence of this method of hardening the surface layer is that under the action of a spark discharge between electrode and blade there is fusion of small sections of electrode and component and simultaneously transfer of material of electrode to the component. Transferred material of electrode, mixed with fused material of blade, will form a layer on its surface. This hard layer is strongly connected with basic material of blade and reliably protects surface of blade from erosion damage. The hardened layer has a rough surface which promotes retention of a film of moisture on the blade and additionally increases erosion resistance.

Fig. 47. Rotor blades of 21st stage of turbine [VKT-100] (ВКТ-100) after 1820 hours of operation.

In article [37] an experiment on stopping erosion damage of rotor blades of the last stages of a turbine at the Kharkov turbine plant VKT-100, calculated on pressure $P_1 = 90$ kgf/cm^2, temperature $t = 535°C$ and pressure in 0.035 kgf/cm^2. The blade of the last stage is 740 mm long, has peripheral velocity 447 m/s and is made of steel 1Kh13. Calculated moisture on exhaust of last stage is 13.6%. Initially special anti-erosion measures were not provided. Inspection of turbine after 1,820 hours of work showed strong erosion wear of blade ends (Fig. 47). The plant at first organized moisture removal (Fig. 48), then hardened blades by the electrospark method. Electrospark treatment of blades was done without disassembling the turbine on an [IAS-2M] (ИАС-2М) assembly by a method developed at the [TsNIITMASh] (ЦНИИТМАШ) and making it possible to obtain a covering from 0.1 to 1.5 mm thick. The materials of the covering were alloy T15K6 (GOST 3882-53), ferrochrome and stellite No. 1. Subsequent tests of the turbine showed that unhardened blades continue to erode (this was observed even after 190 hours of subsequent

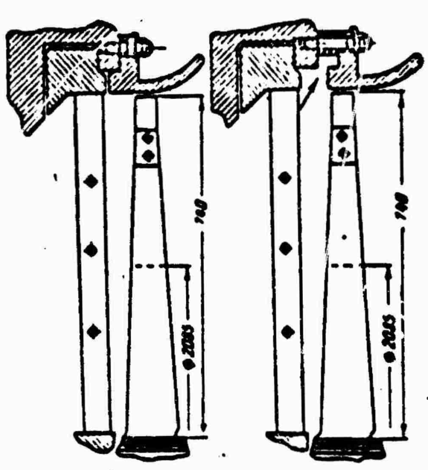

Fig. 48. Organization of moisture removal after the guide assembly of the last stage of turbine VKT-100. a) without moisture removal; b) with moisture removal.

exploitation), but after hardening erosion ceased. Both tests of a natural turbine and tests of models on a plant erosion machine showed that the most erosion resistant is a protective layer from alloy T15K6 on an iron base, in the composition of which is 15% titanium and 6% cobalt.

Results of tests permitted the [KhTGZ] (XTГЗ) to consider the electrospark method of hardening as the basic method of protection against erosion for stages with peripheral velocities of approximately 300 m/s. For higher velocities (near 450 m/s) it is considered rational to use moisture removing devices in combination with electrospark hardening of surface [107].

Application of a hardened layer from T15K6 on leading edges of blades by electrospark method permits increasing period of their service 2-2.5 times [40].

16. Rational Selection of Parameters of Turbine

It is well-known [2] that erosion resistance of blades of steam turbines is determined not only and not so much by vapor moisture with which any stage operates, and by the quality of material from which blades are made but also by good or bad selection of parameters of turbine during its designing. Sometimes in a stage working at 5-7% moisture strong erosion is observed but in a stage of another turbine made of the same material as the first erosion is not observed even at 12-13% moisture. According to the formula of L. I. Dekhtyarev (11) increase of vapor speed at nozzle box exhaust and also decrease of peripheral velocity of blades and angle of entrance of flow into rotor (angle between direction of relative speed and peripheral direction will favorably influence decrease of erosion). These measures promote decrease of force of impact of drop on blade surface. Increase of pressure in a stage without change of degree of moisture and velocity triangles of stage also leads to decrease of erosion.

To decrease erosion of rotor blades of steam condensation turbines it is useful to increase axial clearance between nozzle box and rotor. Quantity of moisture flung off on the housing in the axial clearance will be increased and quantity of drops striking rotor blades will be decreased (see above §§ 3 and 4). At values of angle of departure α_1 less than 20-22° length of zone of full separation is of the same order as span of the blade [125]. It is clear that for stationary turbines with long blades an axial clearance of such dimensions is impossible. However, in certain types of small-size turbines axial clearances of

such order can be acceptable and expedient. Preiskorn [4] considers that the value of this clearance in turbines with long blades should be (0.25-1) b (where b – chord of blade profile).

Inasmuch as erosion of rotor blades promotes secondary drops, forming when film of condensate splits as it converges from blades of nozzle box, it is advisable to assure as little condensate as possible on surface of nozzle blades [4 and 122]. It is desirable to apply profiles with small load and thin trailing edge, and as far as possible to decrease density of nozzle box assembly. Furthermore, it is desirable to avoid connecting shrouds between blades of nozzle box, since condensate settling on these shrouds breaks off in the form of large drops approximately evenly along length of circumference and promotes local erosion of blades of rotor on corresponding radius.

The rotor in contrast to the guide assembly should be made so that condensate precipitates on its blades, under the action of centrifugal forces drops to the housing and is removed in a moisture-removal device placed before the rotor. Active stages from this point of view have an advantage over reactive stages, since with a large curvature of profile of rotor blades, characteristic for active rotors, precipitation of condensate on surface of blades is improved. Thus, once again advantages recognized by many researchers of impulse-type turbines over reactive in anti-erosion qualities (see above § 4) are confirmed. However it is necessary to note that during aerodynamically faultless performance and with application of an effective moisture removal devices reactive stages in condensation turbines is not noticeably inferior to active [122].

It is necessary to select as large as possible an axial clearance between rotor and subsequent nozzle box in order to ensure convenience of collection of accelerated drops of condensate in the water removal channel. The recommended [4] value of clearance is (0.1-0.2) L (where L – span of the blade).

Contours of the meridian section of the flow-through part must be smooth, without steps and protrusions which promote formation of vortices, loss of condensate and, consequently, appearance of sections characterized by increased erosion.

17. Remarks About Electrical Protection Against Erosion

In recent years reports have appeared about experiments in erosion protection using countercurrent [99, 102, and 120], compensating the current appearing during

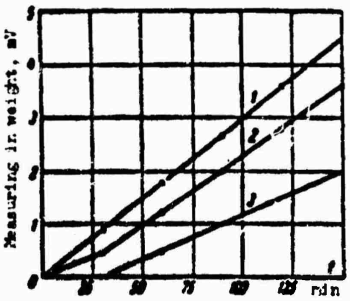

Fig. 49. Dependence of cavitation damage on time. 1 – sample without electrical protection; 2 – compensation of electrical current; 3 – electrical protection by a current of 20 mA.

cavitation (see above § 10) or water-drop impact. This method of protection against erosion is called cathode shielding.

A laboratory check of cathode shielding was conducted on a magnetostrictive vibrator. Effectiveness of protection can be judged from Fig. 49 taken from [99], from which it is clear that by compensation of current appearing during cavitation decrease of erosion damage is attained. Still better results are obtained upon creation of a countercurrent (the part protected against damage should have a negative electrical charge). From Fig. 49 it is clear that cathode shielding only extends the incubation period of erosion damage. It cannot completely protect metal from erosion, since during its application only electrochemical action is retarded; cathode protection does not influence the mechanical action of cavitation.

A check of cathode shielding on a natural hydraulic turbine gave a positive effect only when surfaces of the blades were clean. If, however, blades surfaces were damaged or earlier were subjected to erosion damage, there was no cathode protection [99]. In [120] the beginning of works on cathode protection on steam turbines is reported. However, in this work there are no concrete results of investigations given. Let us note that it is doubtful whether it is possible to expect successful results of work on this method of protection of steam turbine blades from erosion, since the basic role in erosion damage during turbine operation steam belongs to a mechanical factor.

In speaking of electrical methods of protection from erosion, we must mention the proposal [121] to use for removal of drops of moisture from the flow-through part of a turbine electrical drying filter operating on the same principle as Cottrell filters for removal of particles of ashes from exhaust gases. Reports do not indicate practical realization of this method.

CONCLUSION

In conclusion, we give a summation of consideration of the problem of erosion and give a summary of obtained results.

During operation of a turbine stage on moist vapor the condensate will form on the surface of blades of the nozzle box a wavy film which slowly flows from the trailing edges of nozzle blades in the form of drops and flows which spray into drops in the axial clearance between the nozzle box and rotor. Multiple impacts of these drops against the surface of rotor blades is the cause of unique damage, called erosion. Leading edges of rotor blades of stages on low pressure are the most subject to erosion. The impact of a drop against the surface of a rotor blade is greater the greater the peripheral velocity u, angle of incidence into wheel β_1 and mass of drop. Increase of speed of vapor c_1, its density and axial clearance between nozzle box and rotor gives a reverse effect, since it leads to deceleration of the collision of drop with blade and, consequently, to decrease of erosion. Erosion of blades in steam turbines is determined by overall influence of these factors. An attempt at quantitative appraisal of erosion resistance of turbine blades was undertaken in the 1930's by L. I. Dekhtyarev. In the light of contemporary opinions and new facts the theory of L. I. Dekhtyarev requires further development and definitization.

It was determined that there is no fundamental difference between the mechanism of damage of a solid under the impacts of drops at great and small collisior velocities. In each case damage occurs from water hammers against the surface of a part. Only at high collision velocities the impact of every separate drop may cause damage of a part, and dimension of damage will be commensurate with diameter of drop. At low or moderate collision velocities every hydraulic impact appearing upon asymmetric closing of a cavitation bubble at the surface of a part acts on a

microscopically small section of surface; therefore noticeable erosion damage does not appear at once but only after numerous impacts (cavitation bubbles in drops appear even at a collision velocity of 8 m/s). The basic role in erosion damage of blades of steam turbines belongs apparently to hydraulic impacts appearing at asymmetric closing of cavitation bubbles which appear as a drop spreads along the surface of blades. The role of the chemical factor in erosion damage of turbine blades during operation on steam is insignificant.

Different metals resist erosion differently. At present there are no calculation methods for estimating erosion resistance of materials. During experimental laboratory investigation of erosion damage of materials usually the following methods are applied: 1) impact of a stream of liquid against revolving samples, 2) impact of drops or a stream of liquid (moist vapor) against motionless samples, 3) flow of liquid with cavitation at the surface of a sample (cavitation nozzles, slot installations), 4) test of samples on magnetostrictive vibrator, 5) investigation of motionless samples immersed in liquid using a ring-type exciter of oscillations of liquid at surface of sample. Intensity of erosion damage of samples from identical materials depends on selected method of tests. However, if we test a group of different materials by several methods, in erosion resistance they will be in a practically identical sequence independently of method of tests. This rule is explained by the generality of the nature of erosion damage under the impact of drops or streams of liquid and during cavitation in a liquid medium and can be used for free selection of test methods which are convenient in given specific conditions. Hard alloys of stellites and sormite type possess the greatest erosion resistance. Then follows tungsten, hard titanium alloys and chrome-nickel steel. Cast iron, carbon steel, nickel and pure titanium have low erosion resistance; aluminum has the lowest. Within limits of defined groups of materials (for example, carbon or chrome-nickel steel, etc.) erosion resistance is greater the greater the hardness of metal.

Removal of condensate from flow-through part of turbine with help of separational devices, local hardening of sections of blade surface most subject to erosion, rational selection of structural and gas-dynamic parameters of turbine are used to prevent erosion of turbine blades. High effectiveness of moisture removal after the rotor is attained by using a wide and short moisture leadoff with minimum

covering and a certain opening of vane channels of rotor on periphery. It is advisable to give the moisture-removal device before the rotor a smooth entrance (Fig. 46). Effectiveness of this device grows with increase of axial clearance between nozzle box and rotor. In contemporary steam turbines with high peripheral velocities at blade ends an effective combat measure against erosion of blades of last stages is the experimentally proved system of moisture removal in combination with hardening of surface of blades near leading edges by the electrospark method or installation of cover plates from hard alloys (for example, stellite).

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